

Geology of the Castle Hayne Limestone in the Onslow Quarry, Richlands, NC

By

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Abstract

The Eocene age Castle Hayne Limestone Formation on the coastal plain of North Carolina is found throughout Onslow County and is mined at the Onslow quarry south of Richlands. This study characterizes the geology of the rock units present at the quarry, which is located in the western end of the range for the Castle Hayne Formation.

The site has a variable thickness of sandy clay overburden ranging from less than five feet to almost sixty feet. Limestone immediately underlies the overburden and varies in thickness from approximately two feet to greater than one hundred feet. In areas where the limestone is thin, usually less than 10 feet, there is a poorly indurated wackestone (marl) layer. This layer thickens from east to west and its greatest thickness, over fifty feet, is in the north and northwest. The marl is rich in siliciclastics and contains fossils of bryozoans.

The limestone is divided into several distinct layers and in some areas there are interbedded layers of very loosely consolidated carbonate sand. Some of the limestone layers consist of porous grainstone and packstone while others are dense wackestone.

Structural features evident in the limestone layers include cross-beds, lamination and graded bedding. The limestones contain a variety of fossils including bryozoans, echinoderms, gastropods, foraminifera and a few coral fragments. Below approximately 120 and 140 feet below land surface the limestone is replaced by either sand or marl possibly signifying the base of the Castle Hayne Formation.

The limestone layers correspond to the inner and mid-ramp zones of a homoclinal carbonate ramp facies model. Depositional sequences were identified that indicate successive flooding and shallowing upward events. The specific sequences include the inner ramp shoal, inner ramp restricted/open marine and inner ramp open marine facies. The mechanism may be either change in relative sea level or migration of near shore sediments.

Diagenetic features in the rocks include cavities of dissolved bivalve shells, replacement of original shell material, neomorphism of micrite with microspar and spar, syntaxial overgrowths on echinoderms, filling of molds and voids with micrite, microspar and spar, micritic rims, authigenic pyrite and breakage of bioclasts. The diagenetic features change with depth; there is more dissolution of micritic matrix with depth. Strontium isotope ratios of bivalve shell samples indicate an age for the shells between 48.25 and 49.83 Ma.

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By

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Introduction

Many studies of the coastal plain formations of North Carolina have focused on the Castle Hayne Limestone. This formation is a primary aquifer for the coastal plain. However, this formation is not well studied in some areas. One such area is the Onslow Quarry 4.1 miles south of Richlands (Figs. 1, 2 & 3) in Onslow County where limestone thought to belong to the Castle Hayne is mined. This study was done to determine the geology at the quarry and to assess whether the Castle Hayne is the only formation present, or if other formations such as the Trent, Belgrade, New Bern or Silverdale are also present. An aerial image of the quarry is shown in Fig 4.



Figure 1 – Map of North Carolina Highlighting Onslow County

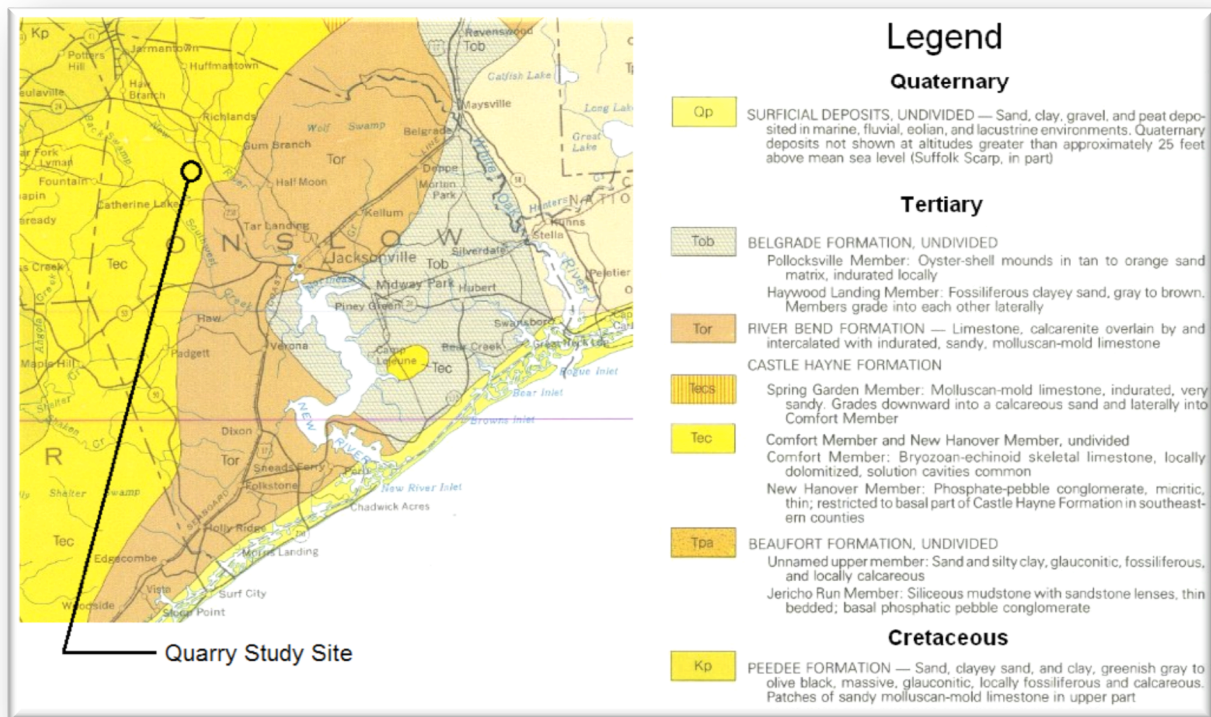


Figure 2 – Geologic Map showing Onslow County – From Geologic Map of North Carolina, NCGS, 1985

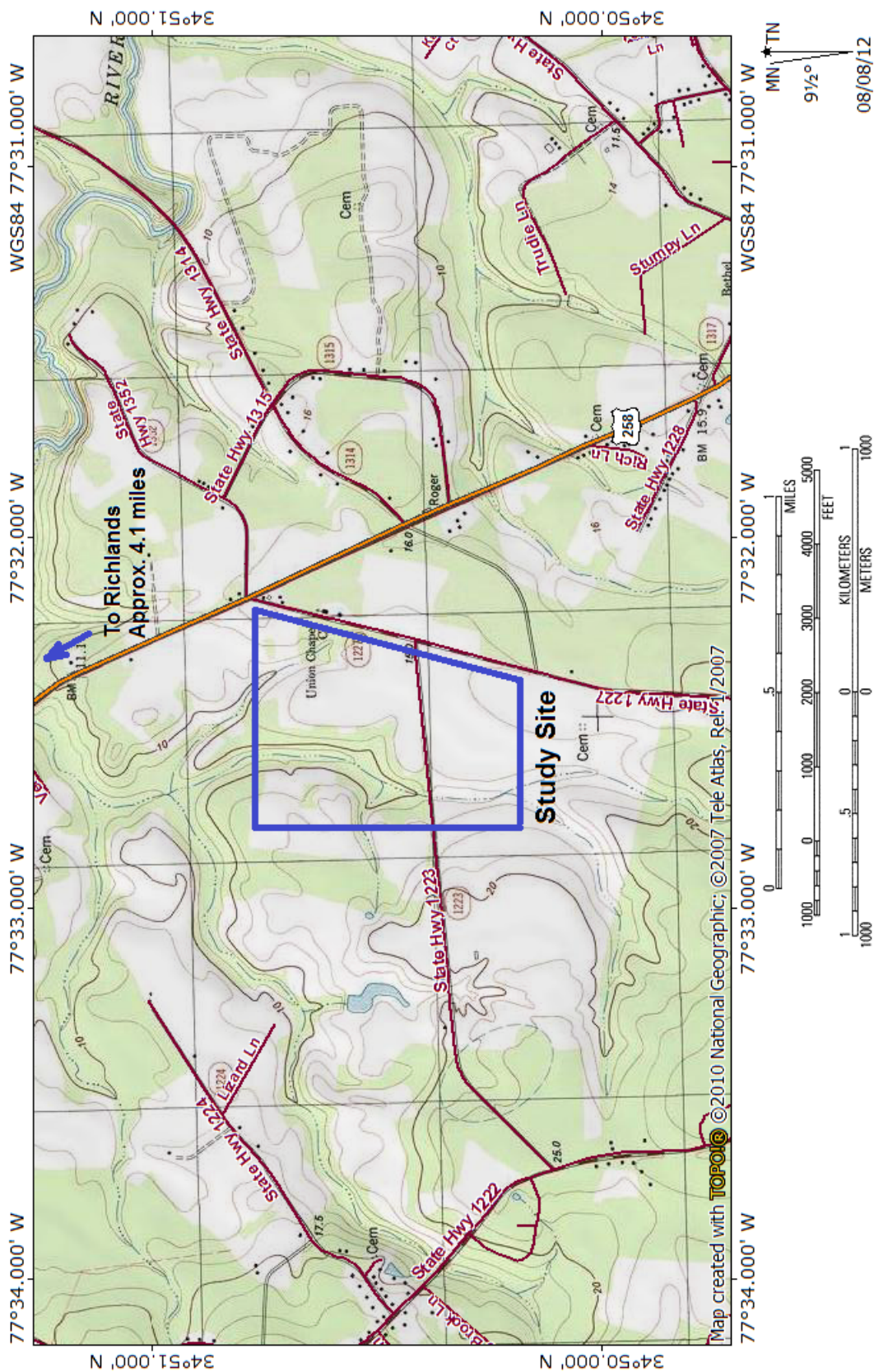


Figure 3 - Map of Study Site



North Quarry

South Quarry

Figure 4 – Aerial View of Quarry Study Site

Previous Studies

Study of the Castle Hayne Limestone began in 1845 when Charles Lyell reported on Eocene age marls and limestones near Wilmington, NC. The formation was first identified as a separate unit in 1912 (Miller, 1912) and named for the town of Castle Hayne where the rock crops out along the Cape Fear River. In addition to the Castle Hayne, Miller identified a second formation thought to be of early Eocene age, the Trent Marl. Miller described the Trent as being composed of calcareous marls, fossiliferous limestone and fine-grained siliceous sandstone. He found the Castle Hayne to contain calcareous marls, fossiliferous limestone and conglomerate. Fossil assemblages for both formations were found to include mollusca, echinodermata, bryozoa, gastropoda and pelecypoda.

The Trent Marl was studied by Harris (1919) and Kellum (1925). In the 1925 study, Kellum determined that based on the fossil assemblage from a study site near Silverdale in Onslow County, the Trent was in fact lower Miocene. Thirty-one additional fossils were identified in the Trent Marl by Richards (1943) and further established the Trent as lower Miocene. The study site for this paper was also near Silverdale. Richards (1948) also recognized the Trent in a paper that examined wells drilled along the coastal plain from New York to Florida. Baum, et al., (1978) have redesignated the Trent as the River Bend Formation and placed it in the Oligocene Epoch.

More recent studies have determined that the Castle Hayne Limestone is the major Eocene formation underlying the North Carolina coastal plain (Brown, 1959; Brown et al. 1972; Ward et al., 1978). The formation has been divided into three members, the lower New Hanover Member, the Comfort Member and the Spring

Garden Member. Below the Castle Hayne is the Paleocene Beaufort Formation and above is either the Oligocene River Bend Formation or unconformably the Miocene Pungo River or Yorktown Formations.

The River Bend Formation is mined near New Bern, North Carolina. This site has been studied by numerous researchers including Thayer and Textoris (1972), Baum et al., (1978) and Rossbach and Carter (1991). The study by Thayer and Textoris (1972) focused primarily on the limestone at the quarry.

The Onslow quarry south of Richlands has been studied previously. Otte (1981) referred to outcrops at the quarry. Coffey (2000) mentioned the quarry in a discussion regarding Paleogene sequence stratigraphy and Coffey and Read (2004) referred to the quarry again in a discussion regarding a subtropical to temperate facies in a Paleogene mixed carbonate-siliciclastic transition zone.

Studies have been done regarding the preliminary stratigraphy of Onslow County but these studies have been mostly confined to the southern and eastern parts of the county. One such study was done by the United States Geological Survey (Seefelt, et al, 2009) using cuttings from a core drilled in October and November, 2006 near Dixon, NC. This well penetrated to a depth of 1,010 feet, and bottomed in the Upper Cretaceous Pleasant Creek Formation. The Castle Hayne Limestone was evident from 233.3 to 276.9 feet below the surface. Directly overlying the Castle Hayne was a 139.2 foot section of the Oligocene River Bend Formation and above that a 22.7 foot section of the Oligocene Belgrade Formation.

The USGS has also created a general hydrogeologic framework map for Onslow County (Fine, 2008) using 123 wells and boreholes. This study, which focuses on the

hydrostratigraphy rather than the lithostratigraphy, shows no indication of the Castle Hayne, River Bend or Belgrade formations in the area near Richlands, NC. Fine's study used information from a previous study also done by the USGS in 1996 by Winner and Coble who developed a hydrogeologic framework for aquifers in the North Carolina Coastal Plain.

The North Carolina Department of Environment and Natural Resources Division of Water Resources created a hydrogeologic framework for the East Central Coastal Plain (Lautier, 2009) but this study does not include Onslow County; it does however describe formations found in Onslow County.

Methods

Cross Sections

Cross sections of the site were created using data from boreholes drilled by the quarry operator (Fig. 7). A cross section of Eocene and Oligocene strata in Onslow County was also created using data from USGS boreholes as described by Brown, et al, 1972 and Seefelt, et al, 2009. The coordinates of the borehole locations are shown in Table 1.

<i>Borehole</i>	<i>Latitude(N)</i>	<i>Longitude(W)</i>
NC-ON-OT-11	34.900000	-77.395833
NC-ON-OT-22	34.658333	-77.480556
NC-ON-OT-23	34.700000	-77.533333
NC-ON-OT-24	34.697222	-77.537500
NC-ON-OT-25	34.550000	-77.375000
NC-ON-T-27	34.825000	-77.529167
NC-ON-OT-28	34.672222	-77.505556
USGS Dixon Core	34.559722	-77.448333
Intersection of Union Chapel Church Road & Duffy Field Road	34.840278	-77.537889

Table 1 – USGS Borehole Coordinates

Field Sampling

Twenty two samples of representative strata were collected from the quarry. GPS coordinates were also determined for each of the sampling locations (Table 2). Samples were also collected from a borehole being drilled at the quarry. Thin sections were made and described from twenty one of the twenty two field samples collected from the quarry.

Hand Specimens

Each sample was cataloged and examined. Results of the hand specimen examination are included in Table 3 and Appendix C. Hand specimens were classified

using the Dunham (Dunham, 1962) classification system. The depth below the top of the rock for the SL samples is indicated as a suffix after the SL location. As an example, SL1-15 indicates that the sample was taken 15 feet below the top of the rock at sampling location 1. The TSL samples were collected from the top surface of the rock with the exception of TSL4-6 which was collected 6 feet below the top surface. Sample TSL3+100 was collected from a location 100 feet north of TSL3. The sampling locations are shown on Fig. 5.



Figure 5 – Map of the North Quarry and Sampling Locations

Fossils identified during hand specimen examination included bryozoan fragments, bivalve and gastropod molds and echinoderm fragments. Nodules thought to be phosphatic in composition were also evident.

Dunham nomenclature was also used to classify six samples collected from a borehole drilling operation. The classification of these samples is included in Table 4. The depth of each sample below the land surface is indicated as a suffix number.

Sampling label	Latitude(N)	Longitude(W)	Notes
SL1-15	34.84397	-77.5398	North wall – 15 feet below top of rock
SL1-35	34.84397	-77.5398	North wall – 35 feet below top of rock
SL2-40	34.84372	-77.53909	East wall – 40 feet below top of rock
SL3-18	34.84415	-77.54032	North wall – 18 feet below top of rock
SL3-25	34.84415	-77.54032	North wall – 25 feet below top of rock
SL3-30	34.84415	-77.54032	North wall – 30 feet below top of rock
SL4-15	34.84404	-77.54124	West wall – 15 feet below top of rock
SL4-25	34.84404	-77.54124	West wall – 25 feet below top of rock
SL5-55	34.84251	-77.54121	West wall – 55 feet below top of rock
SL5-70	34.84251	-77.54121	West wall – 70 feet below top of rock
SL5-70R	34.84251	-77.54121	West wall – 70 feet below top of rock
SL6-80	34.84313	-77.5406	Bottom floor of active quarry
SL6-98	34.84313	-77.5406	Below waterline – 98 feet below TOR
TSL1	34.84191	-77.54143	Southernmost sampling location
TSL2-SL4	34.84404	-77.54124	Directly above SL4
TSL3	34.84301	-77.5415	100 feet north of SL3
TSL3+100	34.84329	-77.5415	100 feet north of TSL3
TSL4-6	34.84415	-77.54032	6 feet below top of rock
TSL4-SL3	34.84415	-77.54032	Directly above SL3
TSL5	34.84397	-77.5398	Directly above SL1
HS1-55	34.84362	-77.54013	Ledge – 55 feet below top of rock
HS2-65	34.84373	-77.54013	Ledge – 65 feet below top of rock

Table 2 – Samples and Geographic Coordinate Locations

Thin Sections

Each thin section was classified using the Folk (Folk, 1962) classification system. Matrices identified include primarily micritic and primarily spar or microspar. A description of each thin section is included in Appendix B.

The maximum depth of samples from the quarry was 98 feet below the top of the rock, approximately 120 feet below the land surface. Due to erosion of upper level strata it may have been deeper in the formation in the past. This would indicate that the samples have only been in the eogenetic and upper mesogenetic diagenetic realms according to the Choquette and Pray (1970) naming convention. Using the James and

Choquette (1983) convention, the deposits would have been in the seafloor and shallow-marine subsurface, meteoric and upper deep surface regimes. Although the diagenesis of each sample can be described according to the individual features such as micrite, calcite, silica, etc. it is preferable to describe the diagenetic changes as they occur with increasing depth.

Twenty thin sections were examined for fossil assemblages, matrix, intraclasts and diagenetic features. A point count was also done for echinoderms, bryozoans, bivalves, gastropods, foraminifera, matrix, quartz, glauconite, other intraclasts and unidentified bioclasts for each thin section. Included in the *other intraclasts* classification are sedimentary intrabasinal clasts and isotropic and opaque minerals other than authigenic diagenetic growths. The point counting results are included in Appendix A. Each point count chart includes a linear trend line which indicates the general trend of each counted item with depth. An arithmetic mean of the point count values for each of the six TSL sampling locations was calculated.

Sample	Dunham Classification	Color	Matrix (clay/crystalline)	Porosity	Notes
SL1-15	Wackestone	light gray	very fine crystalline/clay	1-2mm voids	<1mm dark nodules, 1-3mm gastropod shells, 1-3mm bryozoan fans, bryozoan skeletons
SL1-35	Packstone	light to medium gray	very fine crystalline/clay	1-3mm voids	solution seam, bryozoan fan skeletons up to 10mm, small 1mm dark nodules, layering evident, bivalve molds to 5mm
SL2-40	Wackestone	very light gray	fine crystalline	1-3mm voids	bivalve molds to 12 mm, up to 10mm bryozoan skeletal parts, <1mm dark nodules
SL3-18	Packstone	light gray	very fine crystalline	up to 5mm voids	Gastropod skeletal parts to 5mm, bryozoan skeletal parts to 10mm, sand dollars? to 20mm, 1-2mm dark nodules
SL3-25	Grainstone	medium-dark gray	fine crystalline	1-2mm voids	1-2mm dark nodules, gastropod, bryozoan and coral skeletal parts, very loosely bound, crumbly
SL3-30	Packstone	light gray	very fine crystalline	1-5mm voids	bryozoan skeletal parts to 30mm, layering, bivalve molds to 10mm, <1mm dark nodules
SL4-15	Wackestone	very light gray	silt/clay	1mm voids	up to 40mm bivalve shells, layering, up to 1mm dark nodules, up to 4mm bryozoan skeletal parts
SL4-25	Packstone	light gray	fine crystalline	1-3mm voids	5-10mm bivalve molds, layering evident, 1mm dark nodules, when wet bryozoan skeletal parts visible
SL5-55	Packstone	very light gray	fine crystalline	1-4mm voids	up to 10mm bivalve molds, 1-2mm bryozoan skeletal parts, 1mm gastropod shells, 1-2mm dark nodules
SL5-70	Wackestone	light gray	silt/clay	1-3mm voids	1-20mm bivalve molds, 1-20mm bryozoan skeletal parts evident when wet
SL5-70R	Grainstone	light gray	fine crystalline	up to 10mm voids	up to 20mm bivalve molds, 1-4mm dark nodules, bryozoan skeletal parts evident when wet
SL6-80	Packstone	very light gray	silt/clay	no visible porosity	Bivalve molds to 3mm, 1-3mm dark nodules
SL6-98	Packstone	medium gray	fine crystalline	1-2mm voids	layering, bryozoan skeletal parts, 1-3mm dark nodules
TSL1	Packstone	light brown	fine crystalline	up to 5mm voids	up to 20mm bivalve shells and molds, 5mm gastropod molds, up to 10mm bryozoan skeletal parts, up to 2mm dark nodules
TSL2-SL4	Packstone	light gray	very fine crystalline/clay	1-3mm voids	1-2mm dark nodules, layering evident, when wet bryozoan skeletons to 20mm evident, bivalve molds up to 5mm
TSL3	Packstone	light brown	very fine crystalline	1-3mm voids	sand dollars to 40mm, bivalve molds to 35mm, bryozoan skeletal parts to 10mm
TSL3+100	Packstone	light brown	fine crystalline	minimal 1mm voids	bryozoan fan and skeletal parts up to 30mm, bivalve molds to 20mm, <1mm dark nodules
TSL4-6	Packstone	light brown	silt/clay	voids to 10mm	bryozoan skeletal parts to 20mm
TSL4-SL3	Packstone	reddish-brown	fine crystalline	1mm voids	layering, bryozoan skeletal parts to 10mm, bivalve shell parts to 10mm
TSL5	Packstone	reddish-brown	very fine crystalline	up to 10mm voids	bivalve shells and molds to 10mm, gastropod molds to 10mm, bryozoan skeletal parts to 20mm
HS1-55	Packstone	very light gray	very fine crystalline	1-3mm voids	bivalve molds to 20mm, bryozoan skeletal parts to 20mm, gastropod skeletal parts to 5mm, layering, 1mm dark nodules
HS2-65	Packstone	very light brown	very fine crystalline	no visible porosity	layering, 1-5mm bryozoan skeletal parts evident when wet

Table 3 – Field Sample Hand Specimen Analysis

Sample	Color	Dunham Classification	Matrix	Porosity	Notes
DC-28	light gray	Wackestone	silt/clay	1mm voids	bryozoan skeletal parts to 10mm, unidentified bioclasts to 1mm, layering
DC-33	light brown	N/A - Marl	sand/silt/clay	not evident	bryozoan skeletons to 40mm, silty texture
DC-38	light brown	N/A - Marl	sand/silt/clay	1-3mm voids	unidentified bioclasts to 2mm
DC-43	medium gray	Packstone	fine crystalline	up to 10mm voids	bryozoan skeletal parts to 5mm, bivalve molds to 10mm, unidentified bioclast - 20mm, layering
DC-58	light gray	Packstone	fine crystalline	up to 8mm voids	bryozoan skeletal parts to 8mm, bivalve molds to 3mm, layering
DC-59	light gray	Packstone	fine crystalline	up to 4mm voids	bryozoan skeletal parts to 4mm, unidentified bioclasts to 3mm, layering

Table 4 – Borehole Sample Analysis

Photographic Imagery

In addition to the site borehole and USGS borehole stratigraphy analysis, an examination was done of photographic imagery acquired at the site. Fig. 6a shows a graphic created from a photographic image (Fig. 6) taken of the southeast wall of the north quarry. The marl lens, three carbonate sand layers and several limestone layers are present. The marl lens is comparatively thin along the east wall; it is also closer to the land surface than it is in the west. The layers on Fig. 6a were delineated from those evident in the photographic image. The layers indicated below the waterline on Fig. 6a were recognized during field sampling at location SL6.



Figure 6 – Photograph of the Southeast Corner of the North Quarry

The diagram illustrates a geological cross-section with the following layers and features:

- Vertical Axis:** Labeled "Feet Below Top of Rock" with values from -10 to -100.
- Horizontal Axis:** Labeled "TOR" (Top of Rock).
- Rock Layers (from top to bottom):**
 - Limestone:** Represented by light gray areas.
 - Carbonate Sand:** Represented by brown areas.
 - Marl:** Represented by green areas.
- Water Line:** Indicated by a dashed line, showing the boundary between the rock layers and the water-saturated zone.
- Annotations:**
 - An arrow points to the "Top of Rock" (TOR) line.
 - Labels "Limestone", "Carbonate Sand", and "Marl" are placed within their respective layers.
 - A label "Water Line" with an arrow points to the dashed line.

Figure 6a – Graphic Image of Southeast Corner of North Quarry

Results and Discussion

Quarry Cross Section Stratigraphy

The quarry stratigraphy is generally divided between overburden and underlying limestone. The limestone consists of lithified units, unconsolidated carbonate sand units and a poorly indurated wackestone (marl). The overburden, marl and limestone are described below.

Overburden

The drilling crews used hollow stem augers when conducting exploratory coring operations. Depth to the topmost rock layer was recorded in all boreholes thus revealing the site-wide thickness of the overburden, thought to be post-Oligocene in age. The composition of the overburden is primarily reddish sandy clay. The upper section of the east wall of the north quarry shows red staining due to rainwater transporting dissolved iron downward from the overburden.

The thickness of the overburden across the site is generally greater in the southwest than in the north (Fig. 24). The greatest thickness, 57ft, is in borehole K10 (Fig. 7 and Fig. 23) in the southwest and the smallest thickness, 2ft, is at borehole G5 in the northeast (Fig. 7 and Fig. 8).

Poorly Indurated Wackestone (Marl)

The amounts of marl found in the boreholes across the site are highly variable. Marl was absent in many of the boreholes but in others, greater than 50 feet is evident. The borehole with the greatest thickness, 57 ft, of marl was in E1 in the extreme north (Fig. 7 and Fig. 9). The marl thickens from east to west across the site with the greater

thicknesses being in the north and northwest. The marl often occurs as a 20 to 50 foot lens below the first occurrence of limestone and then re-occurs sporadically at approximately depths of 80 to 100 feet. The first marl layer also trends in a downslope direction from east to west. The upper marl layer is delineated on the borehole logs as a sand/marl or marl layer. Fig. 25 maps the marl and sand/marl layer. The sand/marl sequence is confined to a specific area and implies input from a specific, restricted source. There are no specific criteria for the differentiation of the marl, sand/marl, quartz sand and carbonate sand sequences on the borehole logs. The areas where marl is not reported are also shown on Fig. 25. Marl samples DC-33 and DC-38 (Table 4) are rich in siliciclastic silt and fossils, primarily bryozoans. The lower occurrence of marl is inconsistent in the borehole logs. There is also a sand lens southeast of the sand/marl deposit but disconnected from it; this layer ranges from 5 to 10 feet thick. It is possible that the sand does connect to the sand/marl, this is shown as a cross hatch on Fig. 25.

Limestone

The limestone is divided into two distinct units, an upper unit that overlays the marl unit and a lower unit that underlies the marl and overlies the sands and marls of the underlying formation. The two limestone units are shown on Fig. 6a. The upper unit ranges in thickness from less than 5 feet to greater than 90 feet (Fig. 26). The area of greater thickness is also an area where marl is absent.

The lower unit is dividable into several individual members that include carbonate sands and lithified limestone layers. These layers are also shown on Fig. 6a. In

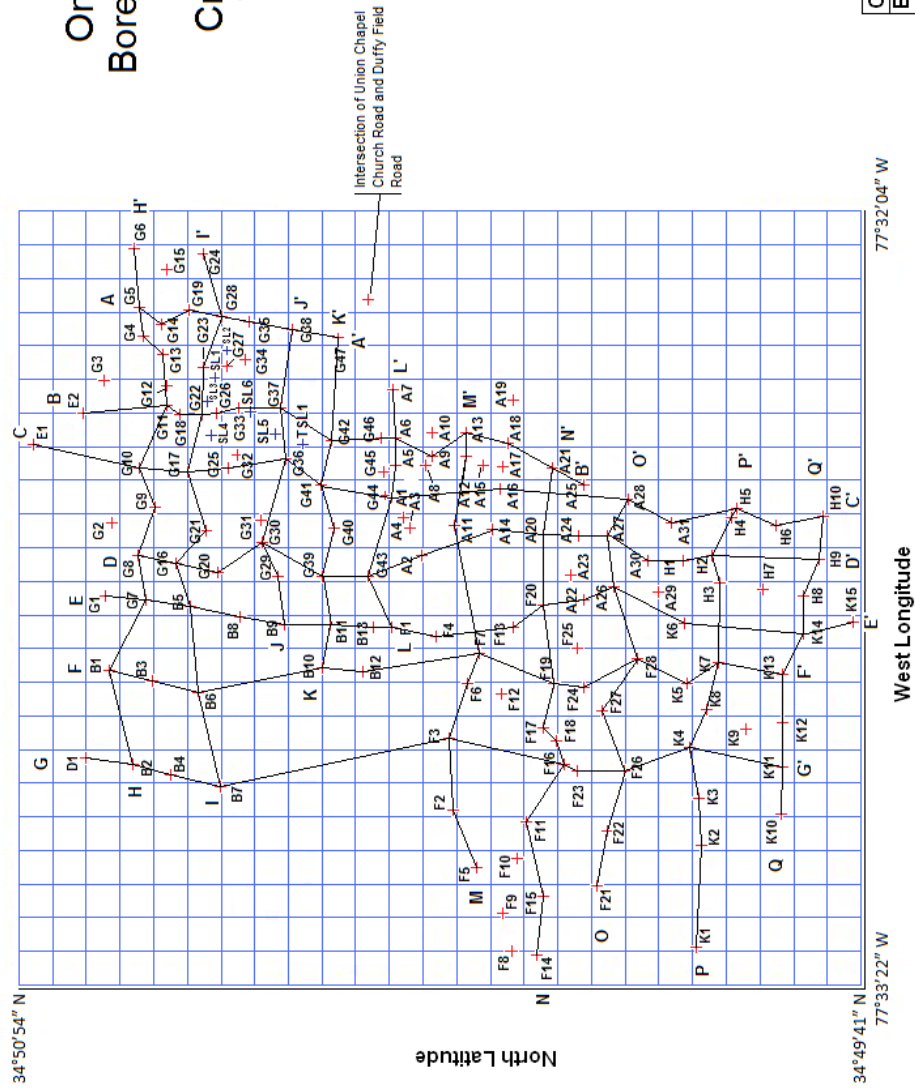
addition a carbonate sand layer and limestone layer occur below the waterline. These two layers were identified during field sampling.

The borehole logs indicate several varieties of limestone in the two limestone units:

- Limestone
- Shelly limestone
- Limestone/shelly limestone
- Sand/shelly limestone
- Sand/limestone
- Clay/limestone
- Marl/limestone
- Shelly limestone/marl

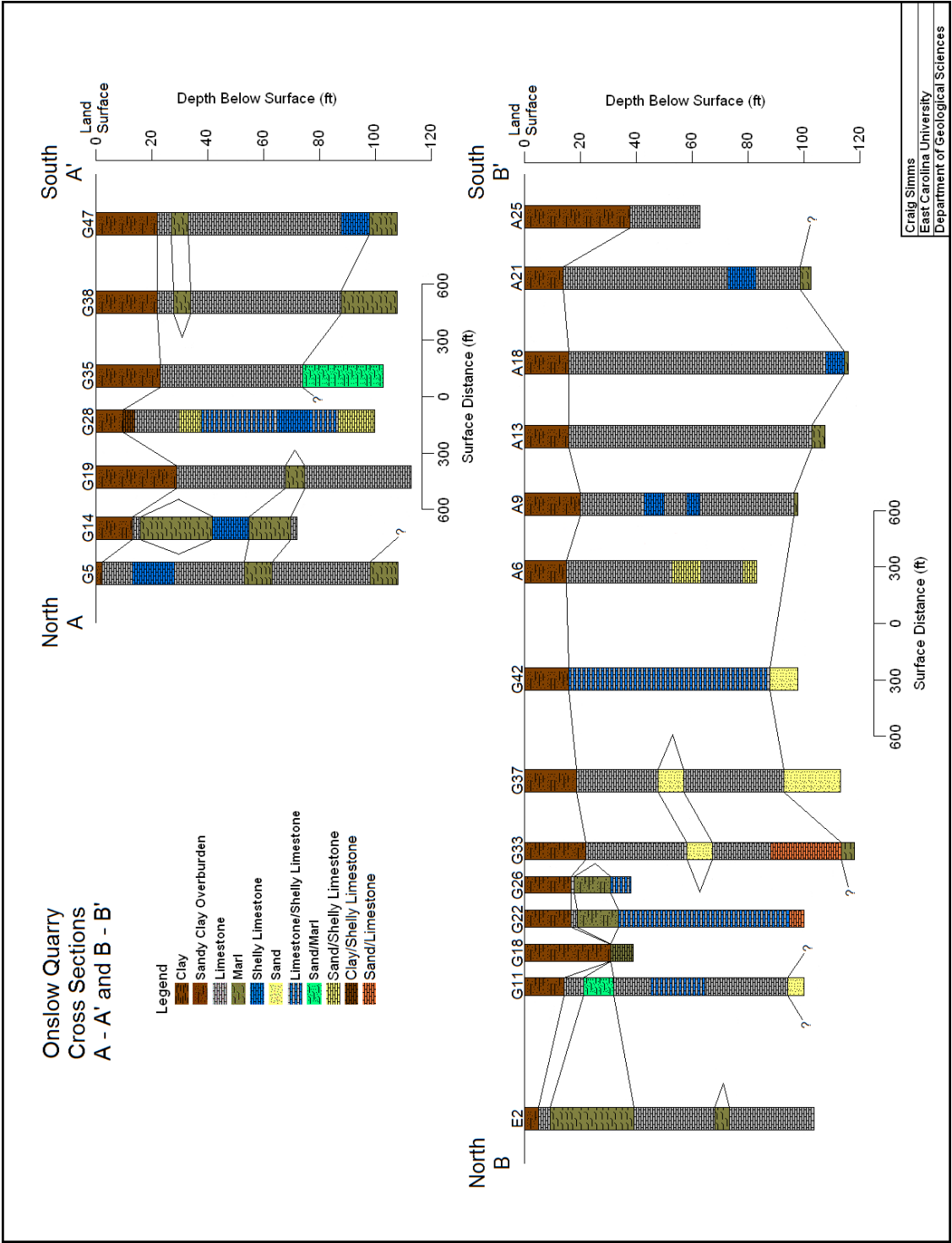
The primary varieties indicated in the logs were limestone and shelly limestone. There was no reference to any specific shell species in the driller logs. The borehole logs do not specify whether the sand is siliciclastic or carbonate. By comparing the amount of sand recorded in the borehole logs with the carbonate sand seen during field study it is probable that the sand as recorded in the logs is siliciclastic. The logs also do not specify whether the limestone is dense or porous. They do indicate that the limestone transition to sand and marl occurs approximately 100 to 130 feet below the surface. This may possibly indicate the break between the Eocene strata and underlying Paleocene or Cretaceous beds.

Onslow Quarry Borehole Locations and Cross Section Transects



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Figure 7 – Study Site Borehole Locations and Cross Section Transects



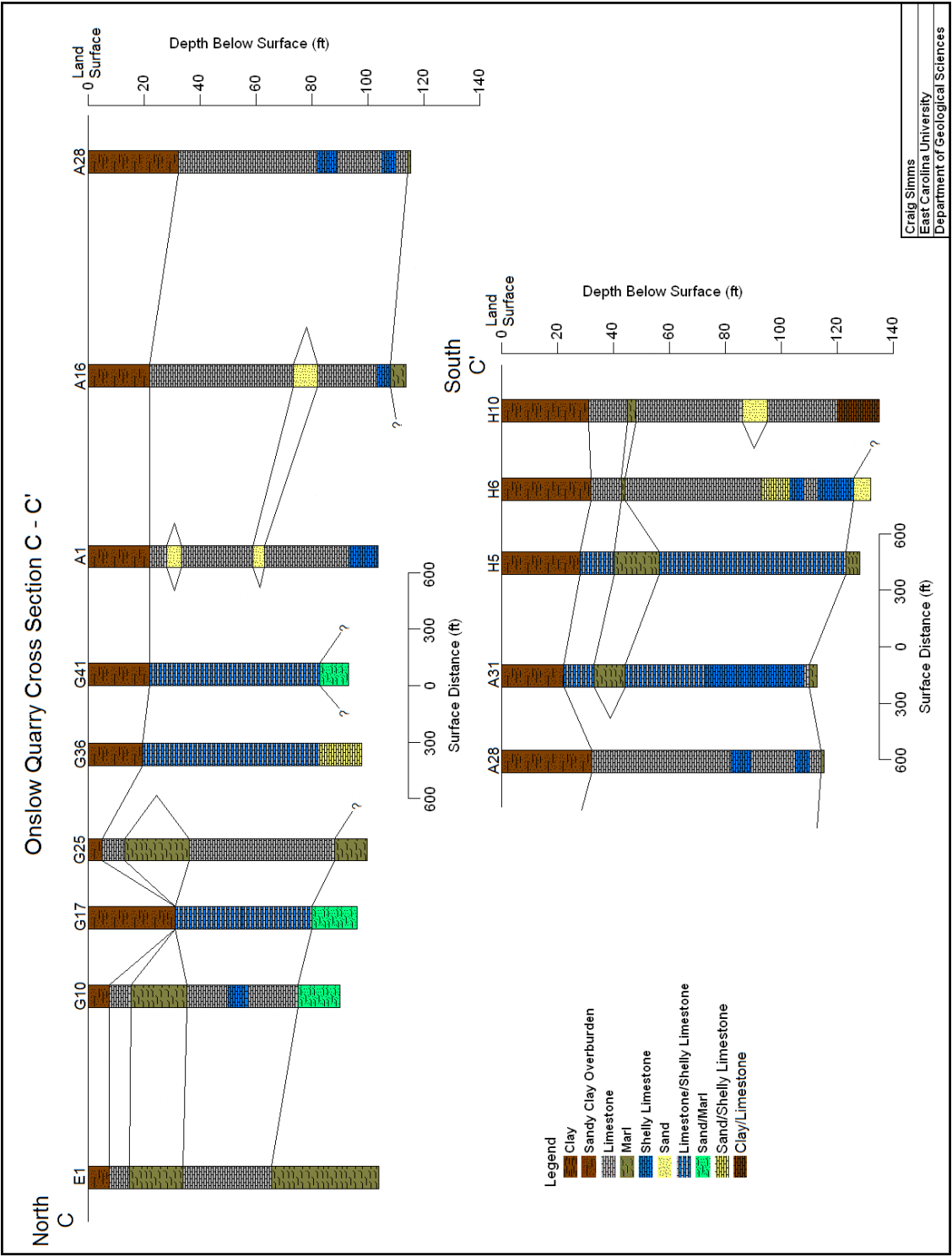


Figure 9 – Borehole Cross Section C – C'

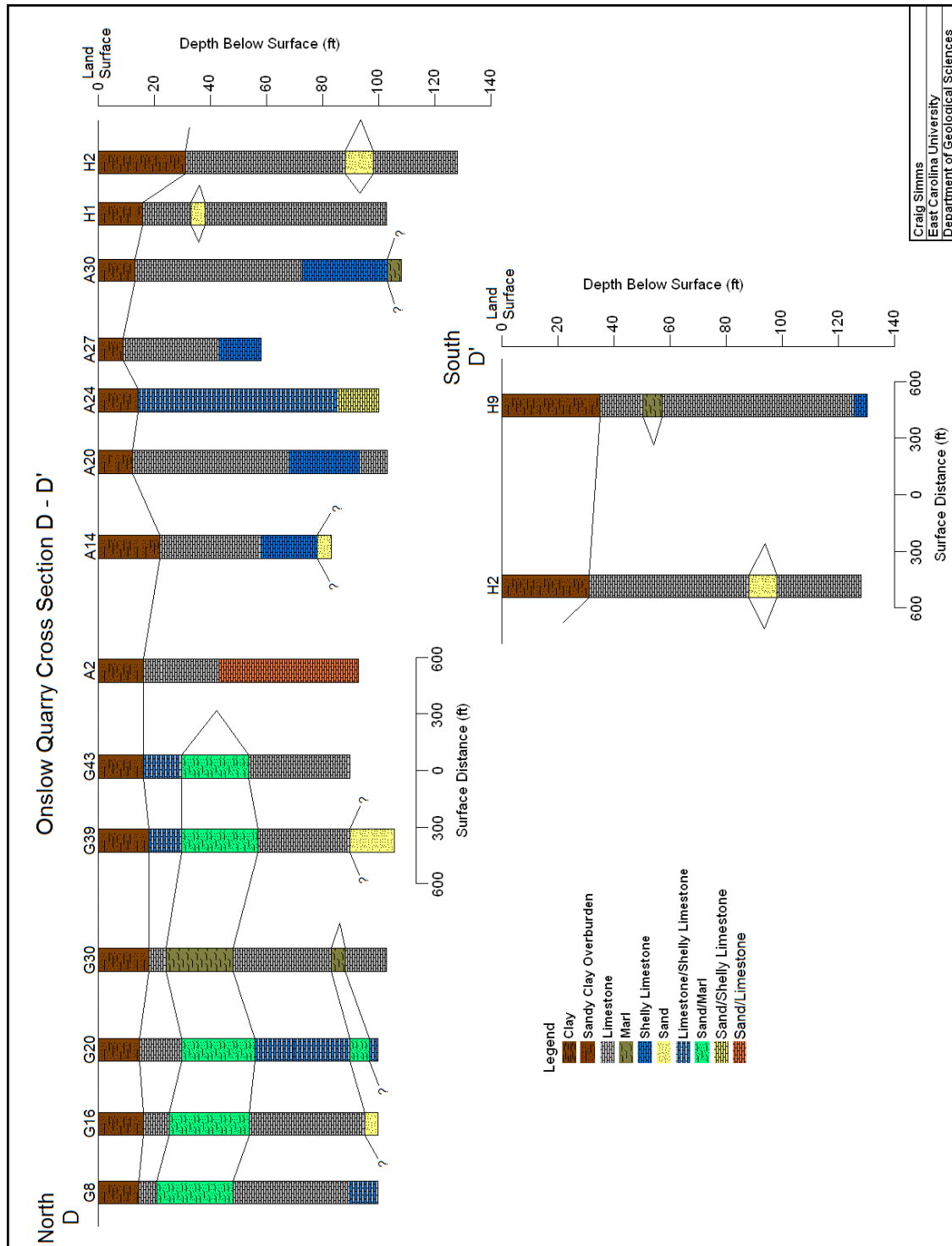


Figure 10 – Borehole Cross Section D - D'

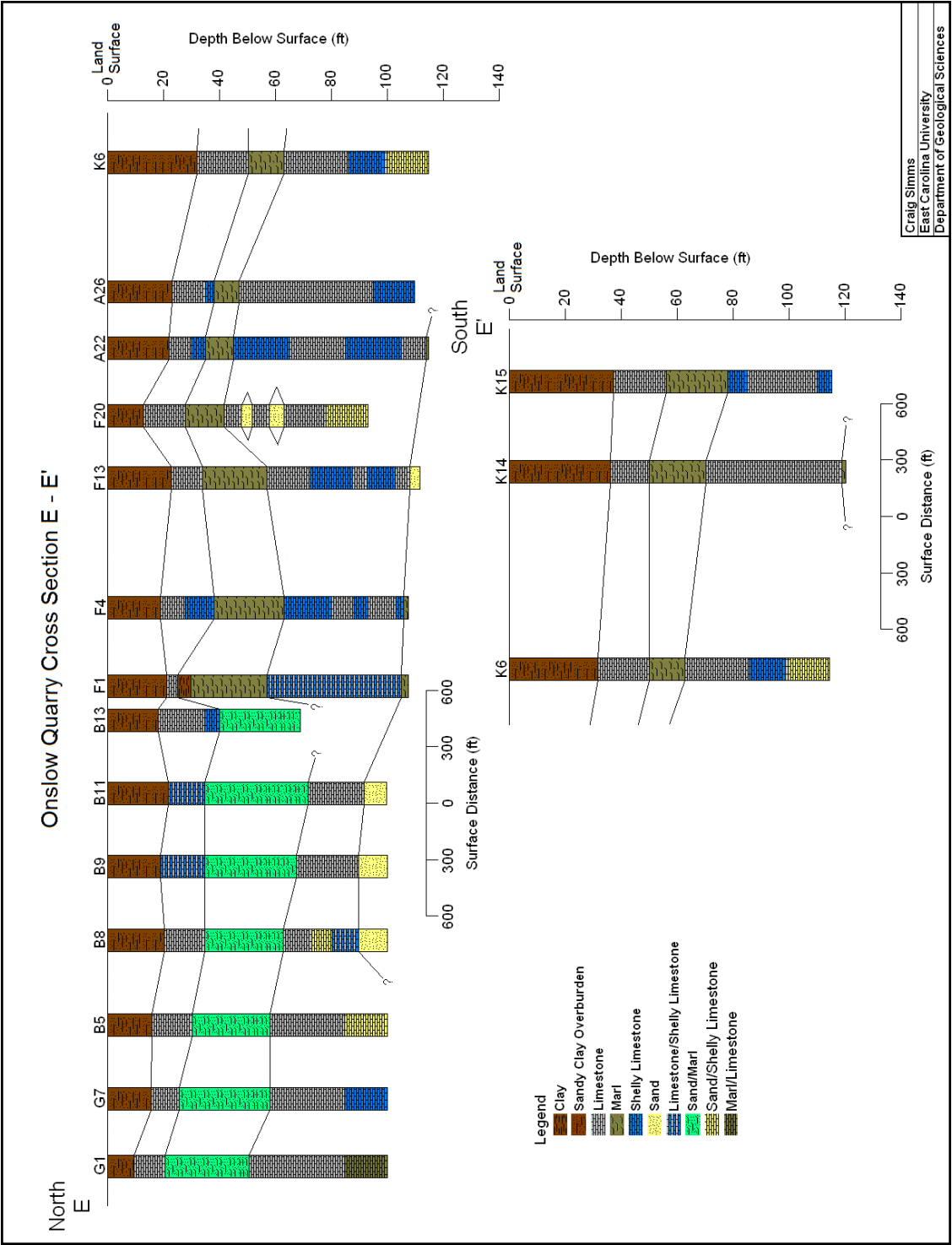


Figure 11 – Borehole Cross Section E - E'

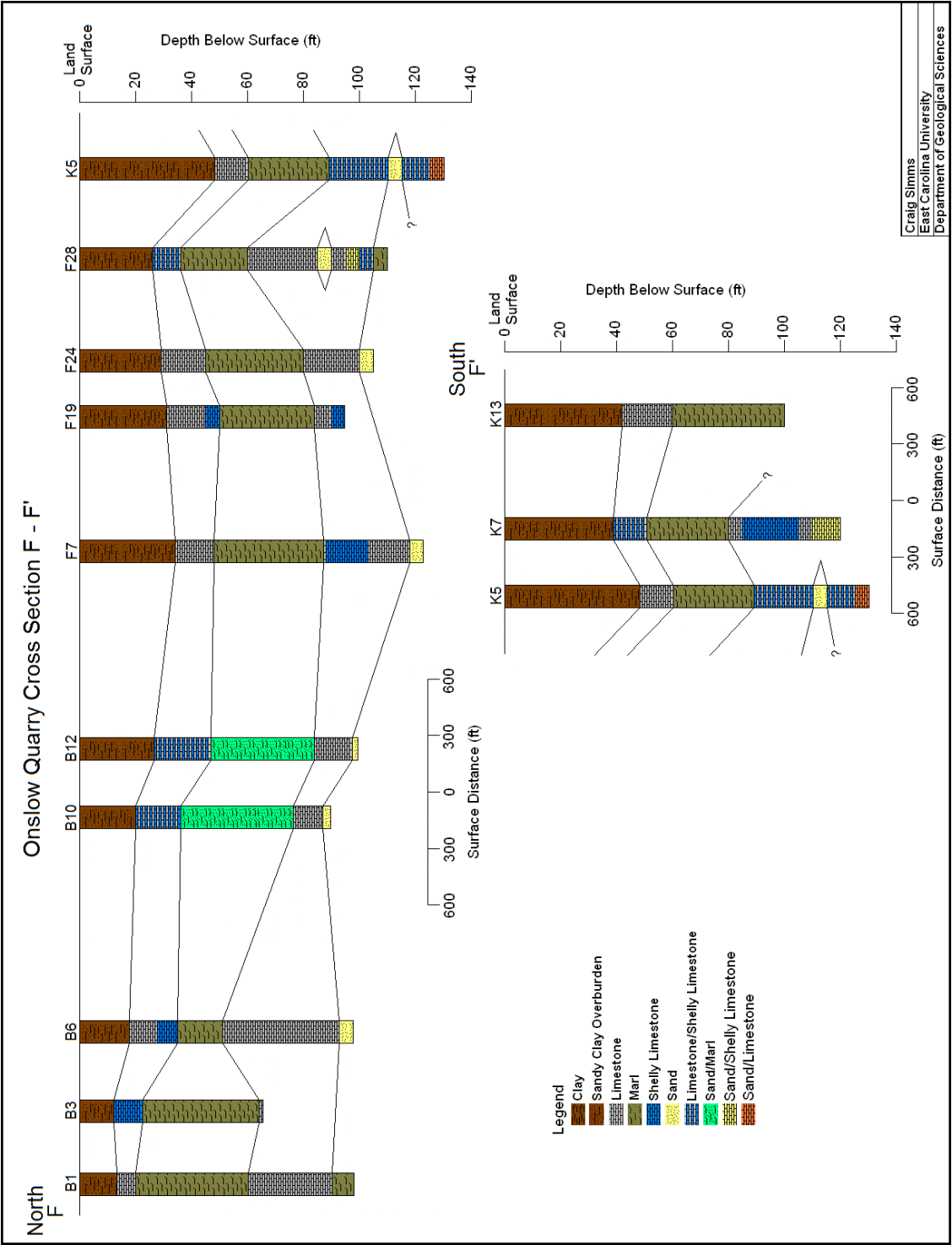
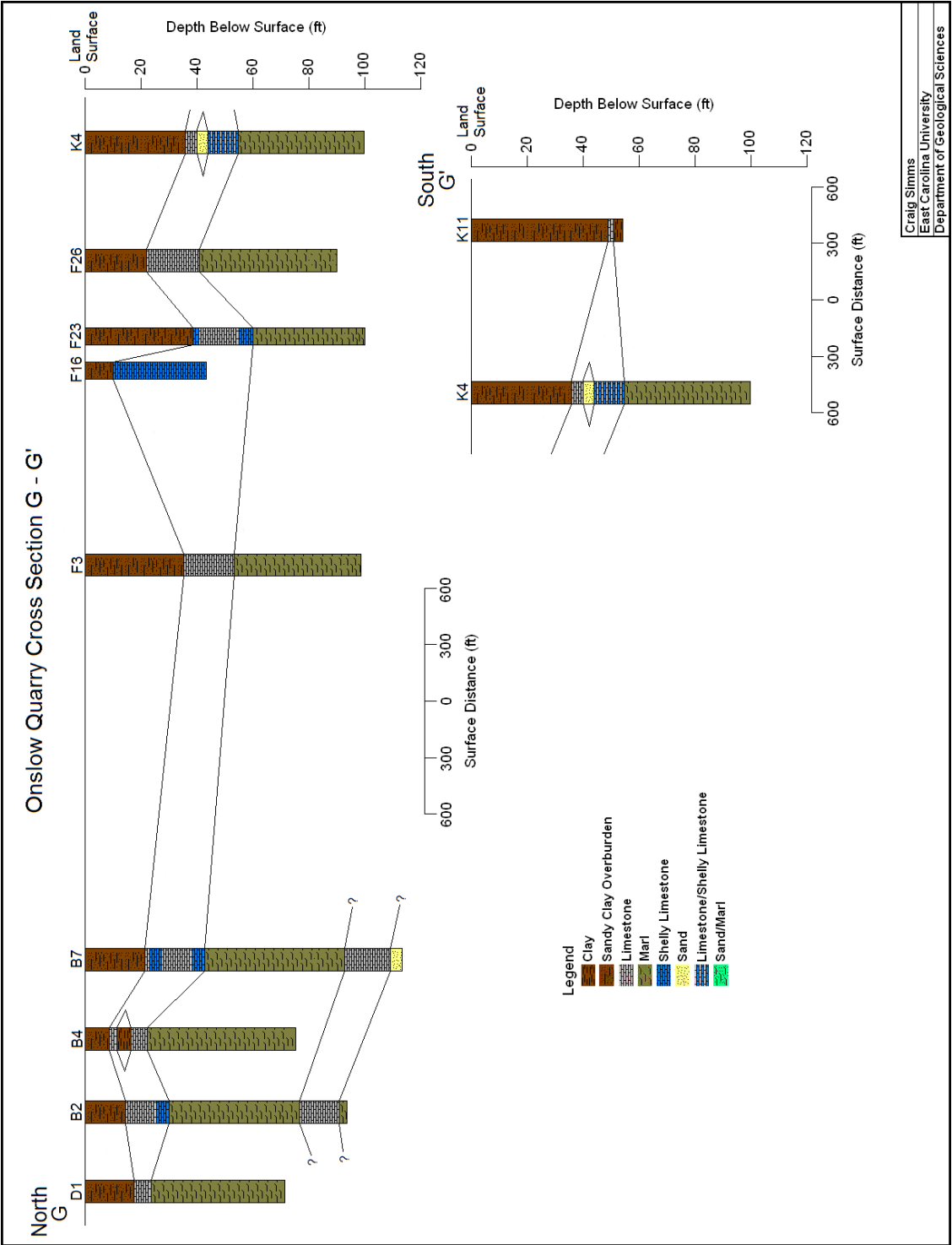


Figure 12 – Borehole Cross Section F - F'



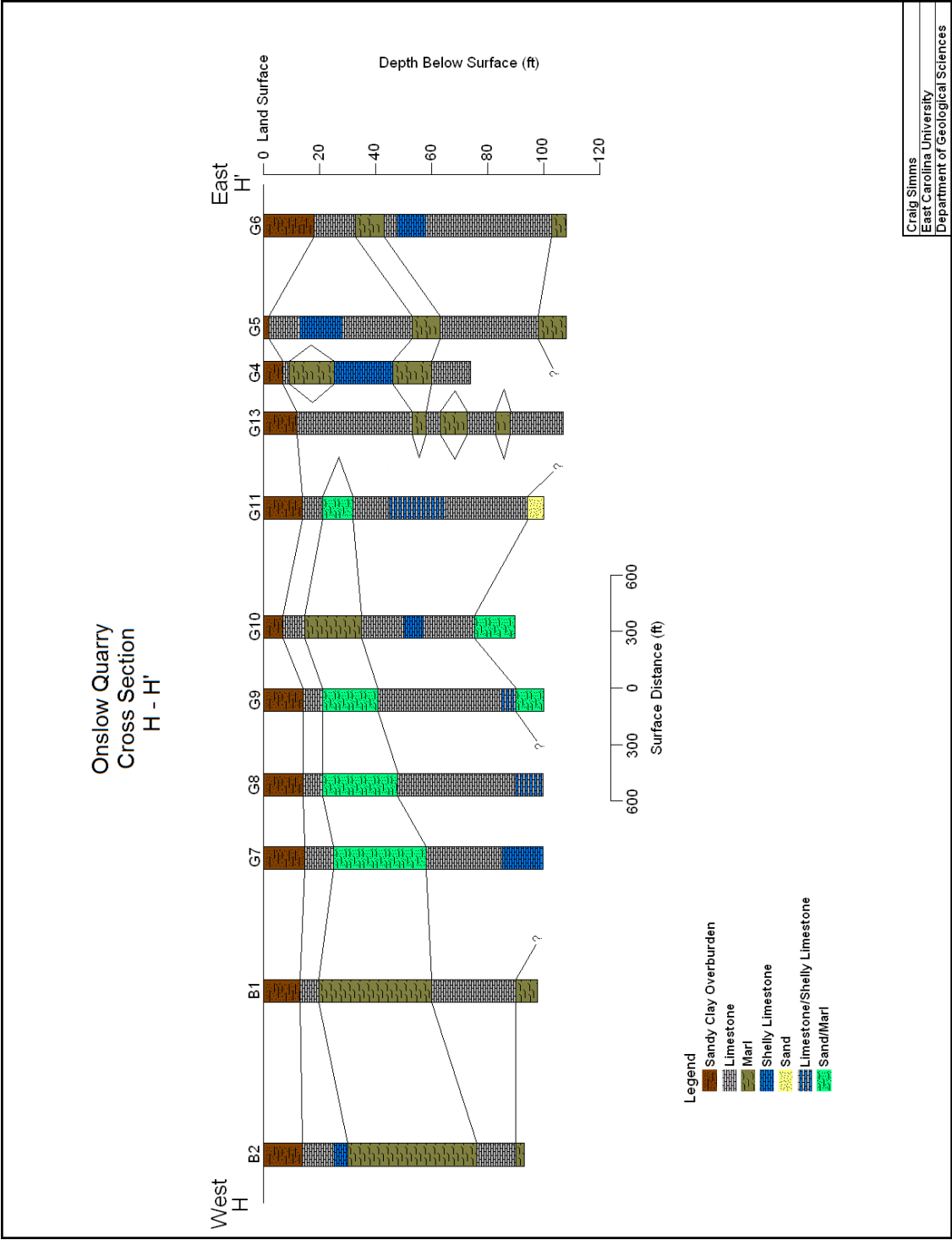
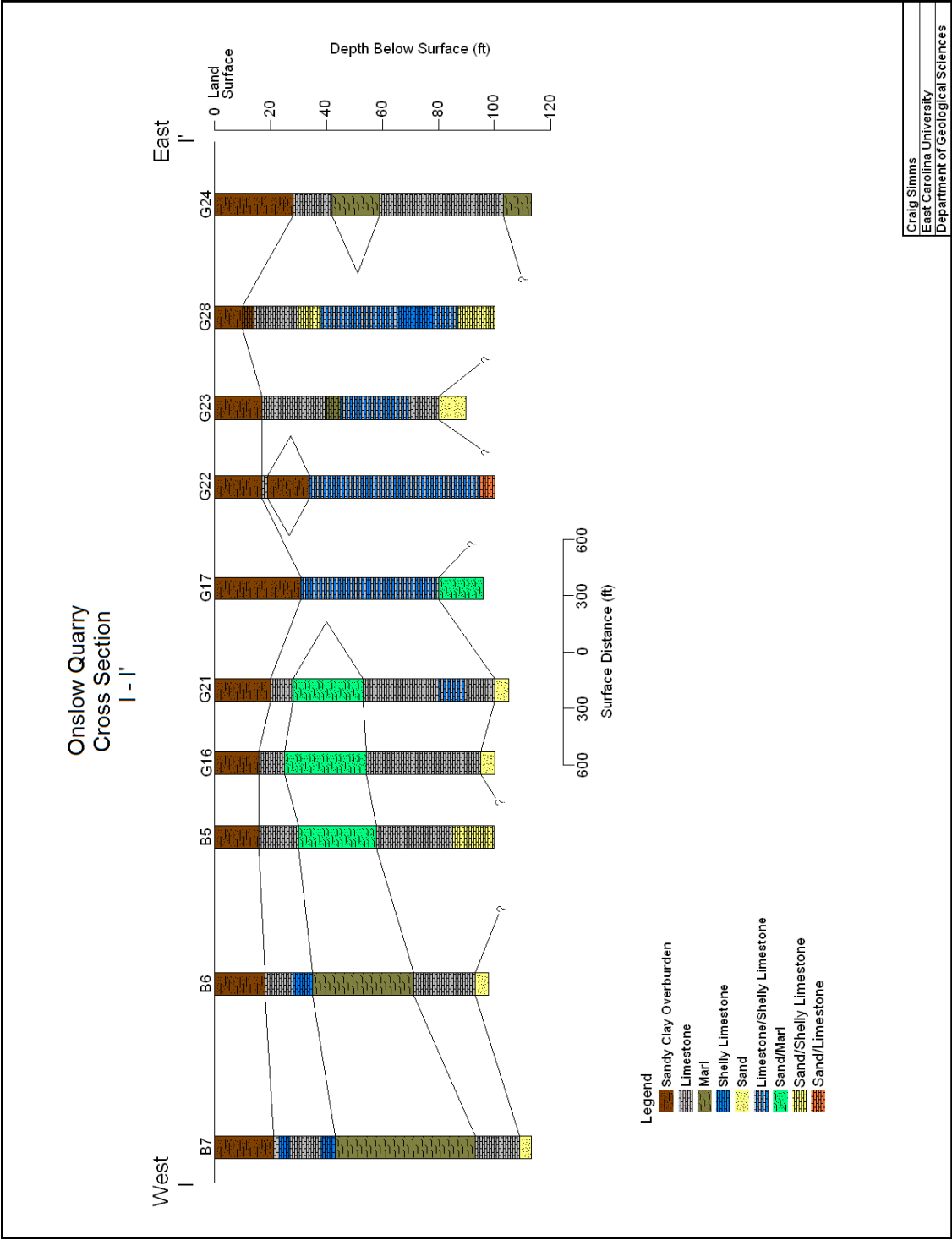


Figure 14 – Borehole Cross Section H – H'



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Figure 15 – Borehole Cross Section I – I'

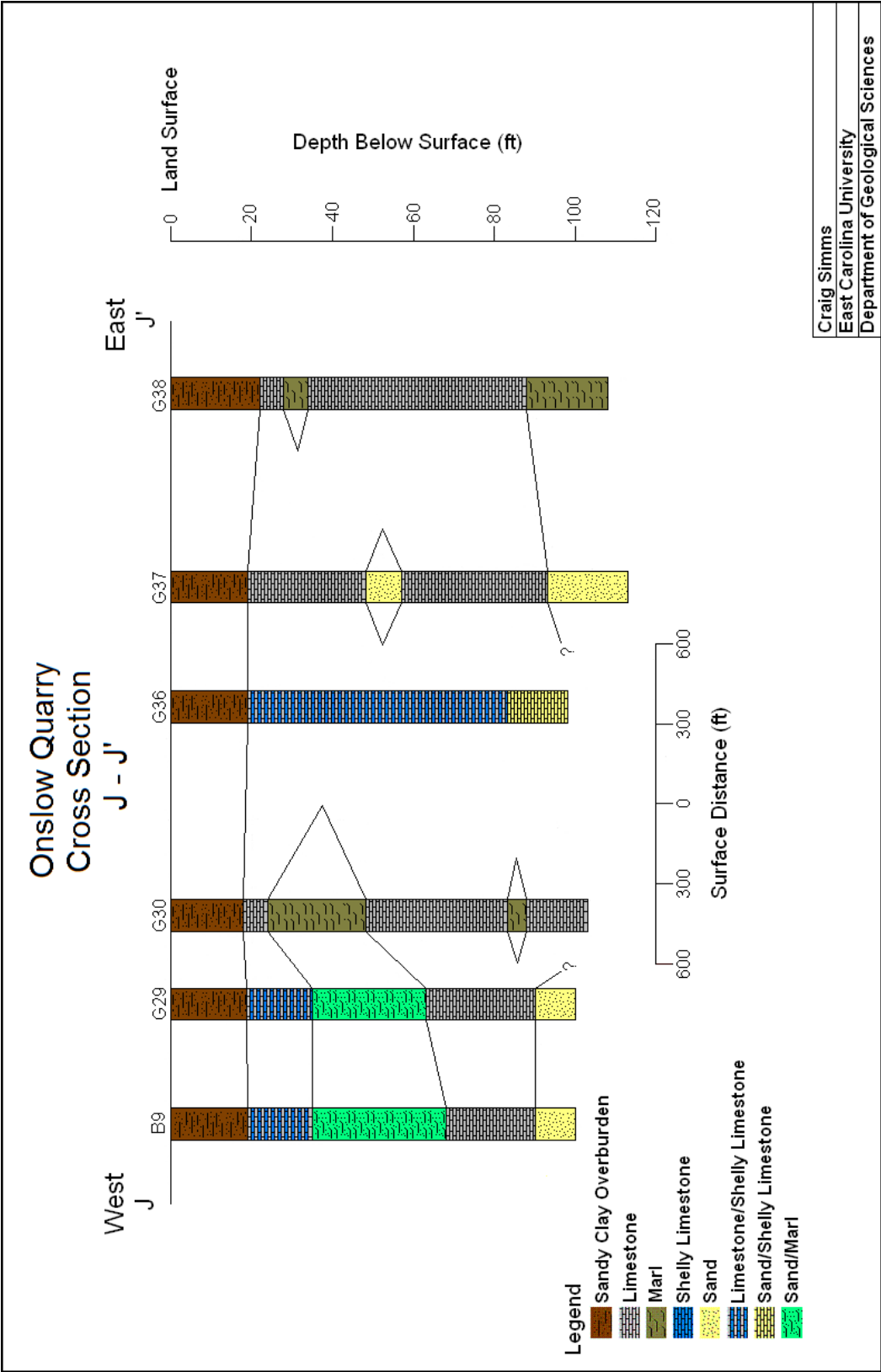


Figure 16 – Borehole Cross Section J – J'

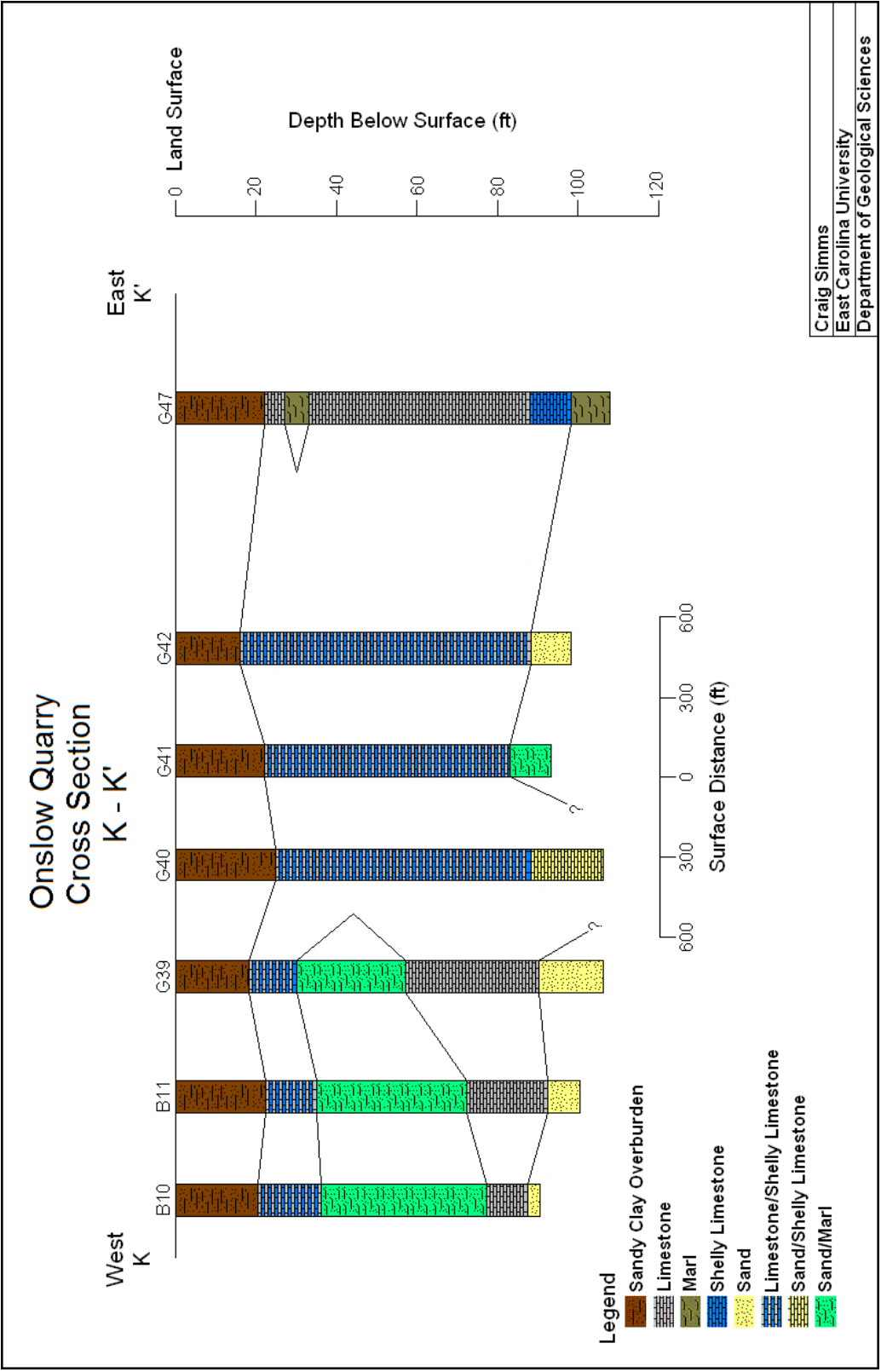
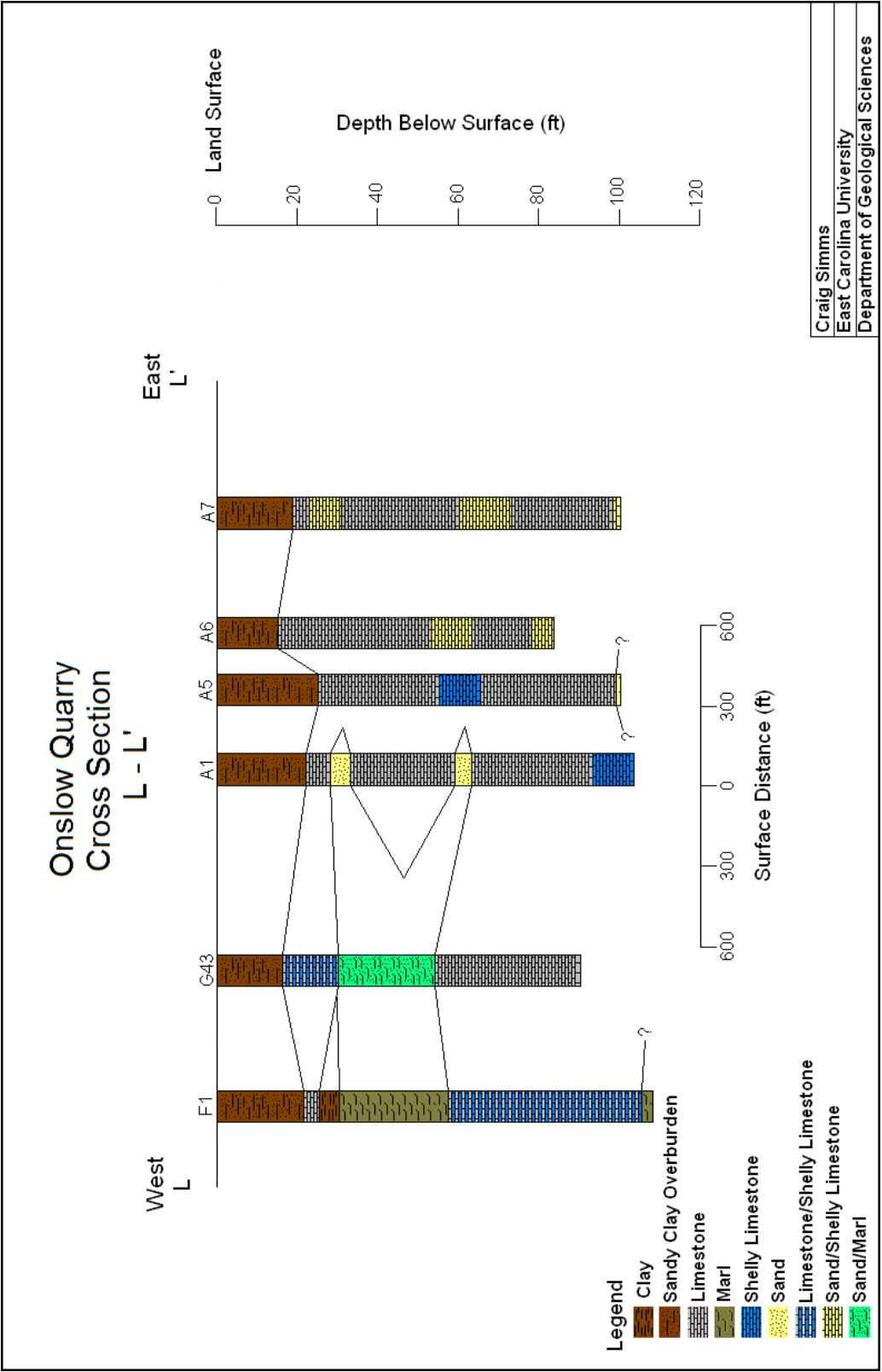
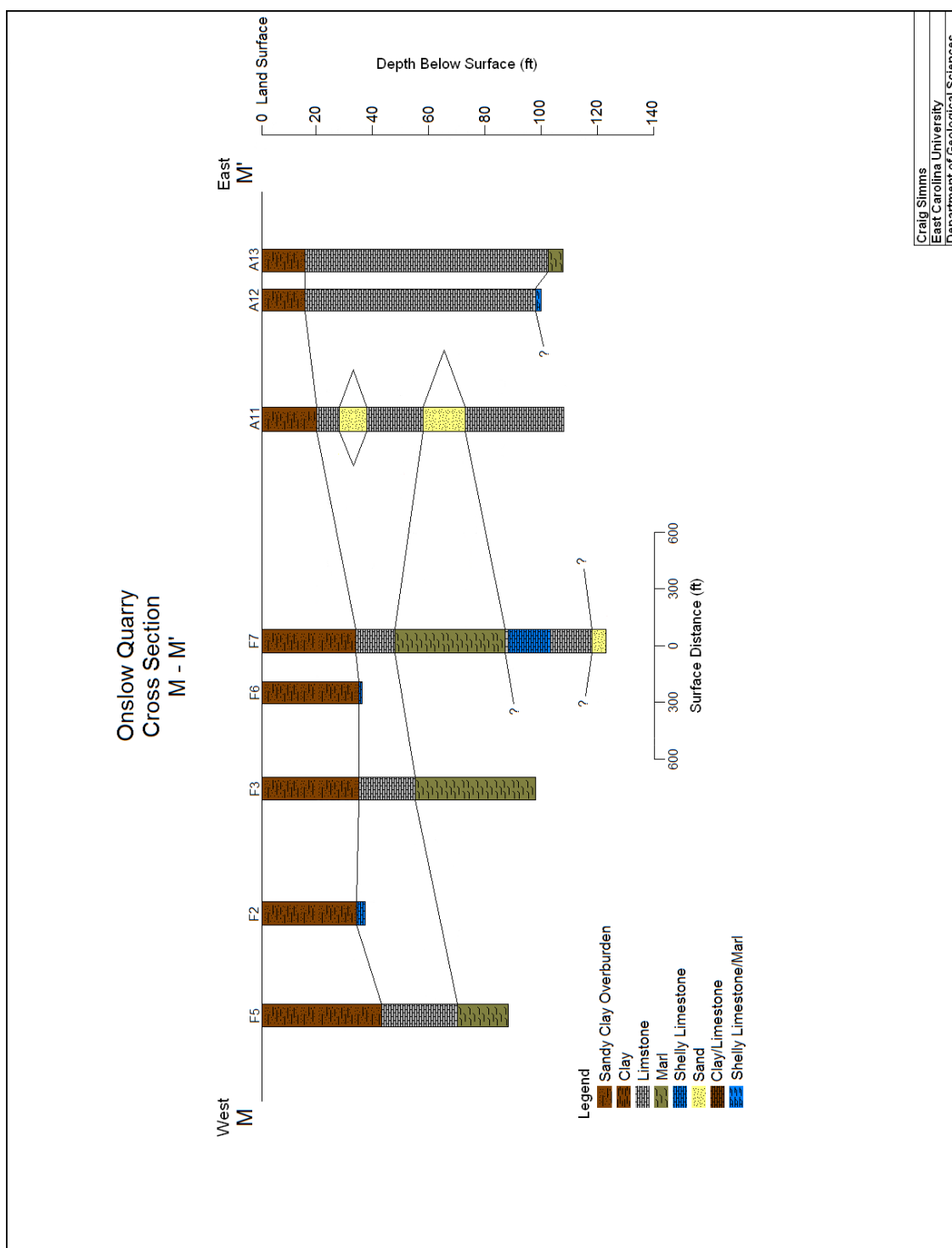
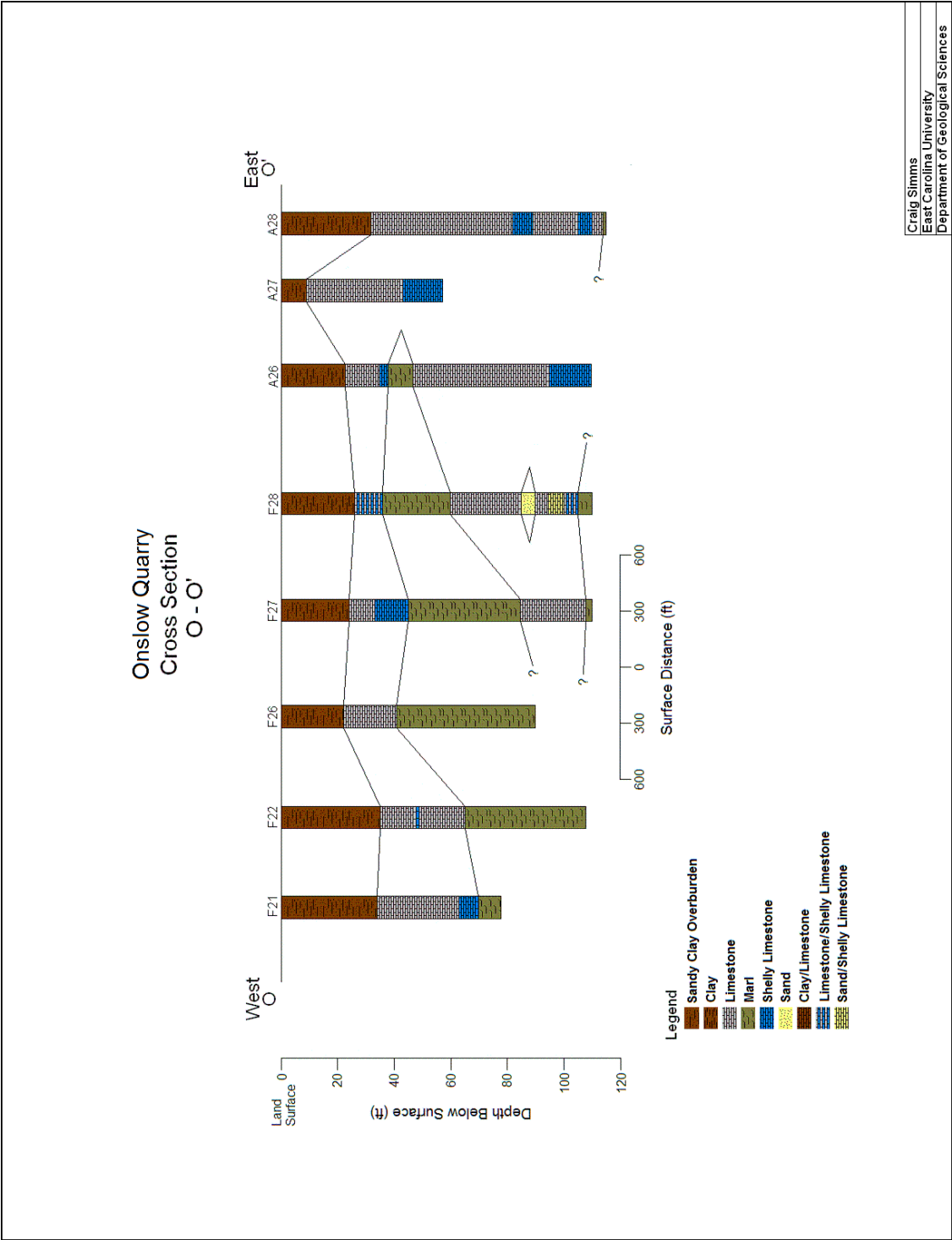


Figure 17 – Borehole Cross Section K – K'



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Figure 21 – Borehole Cross Section O – O'

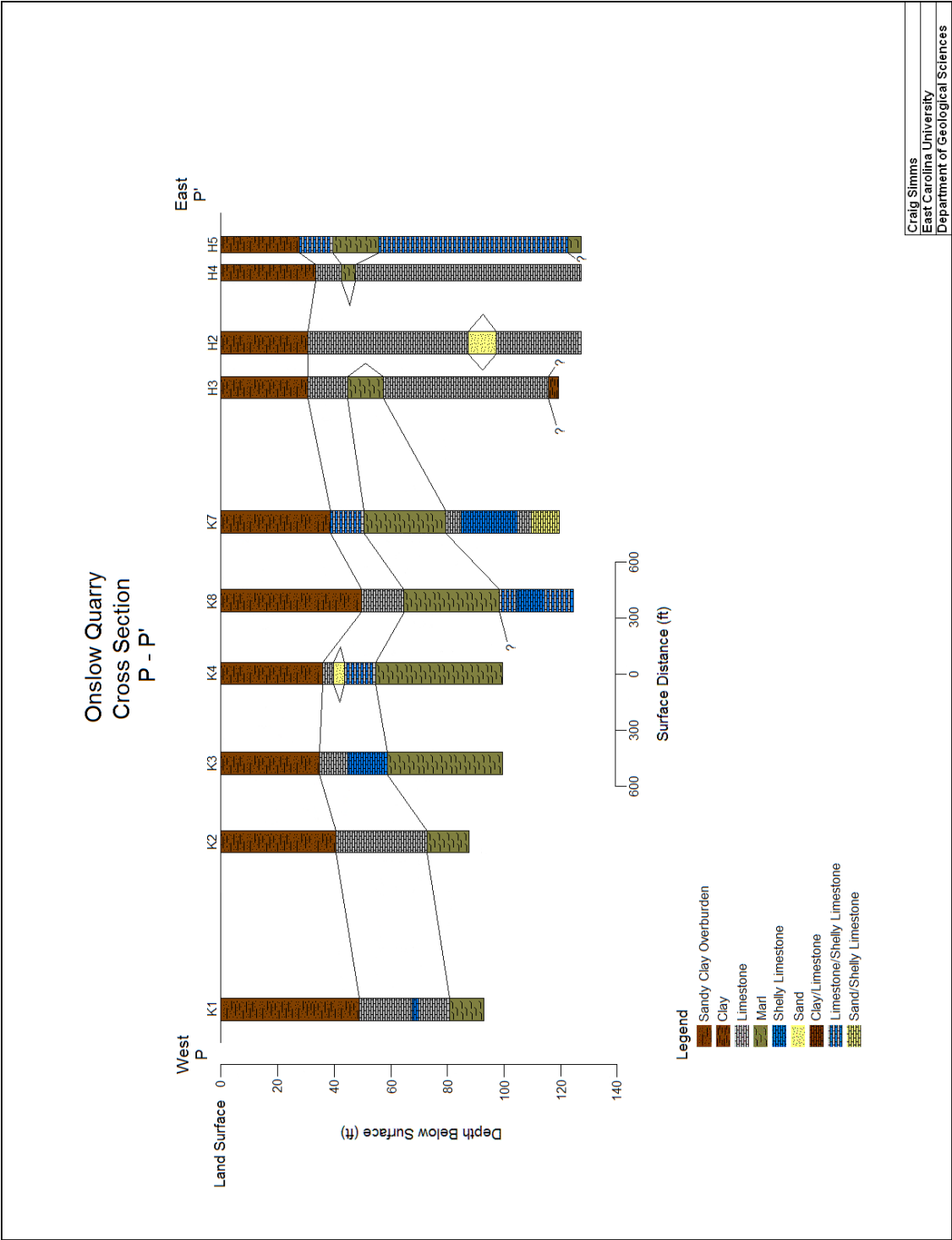


Figure 22 – Borehole Cross Section P – P’

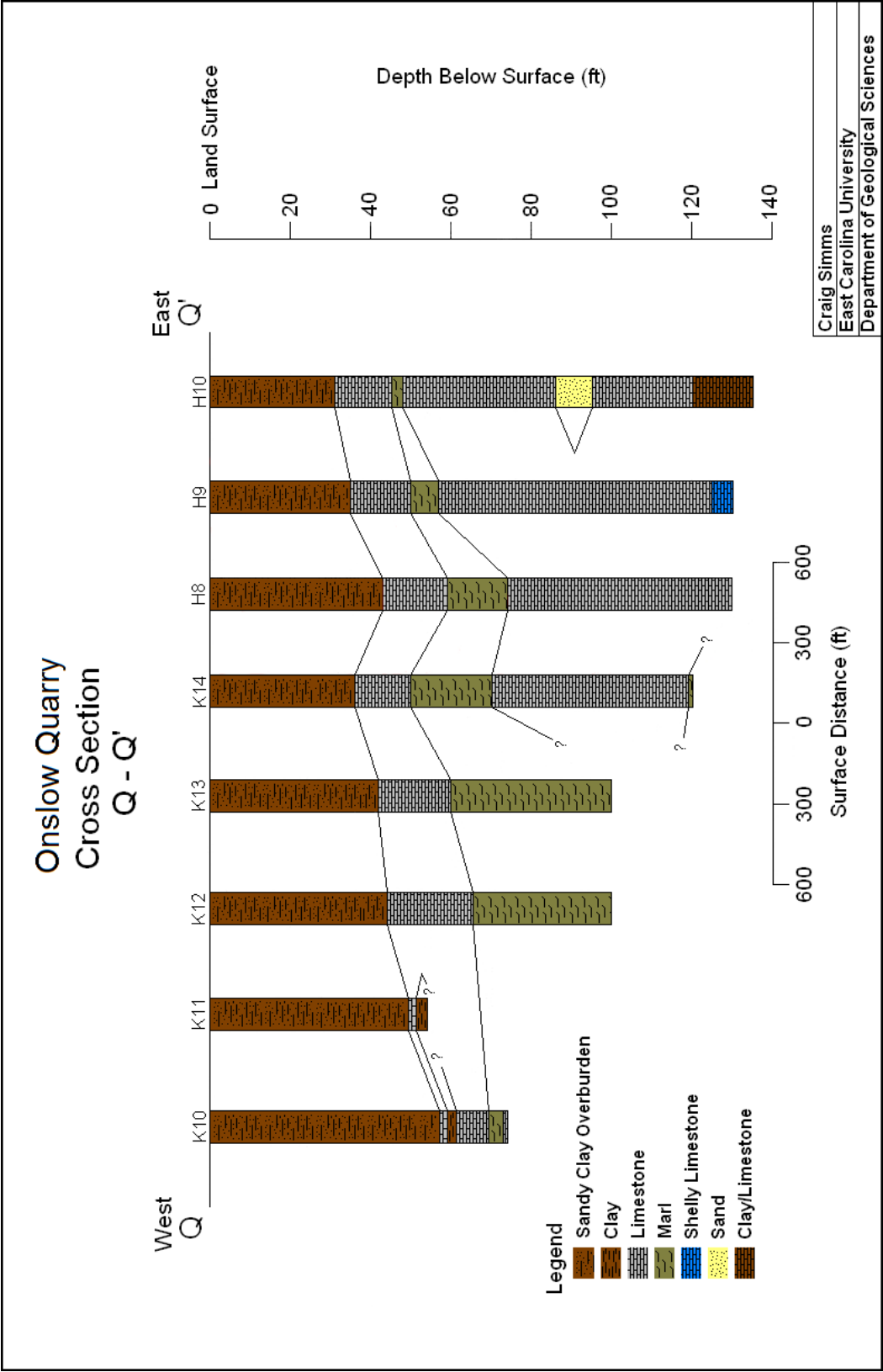


Figure 23 – Borehole Cross Section Q – Q'

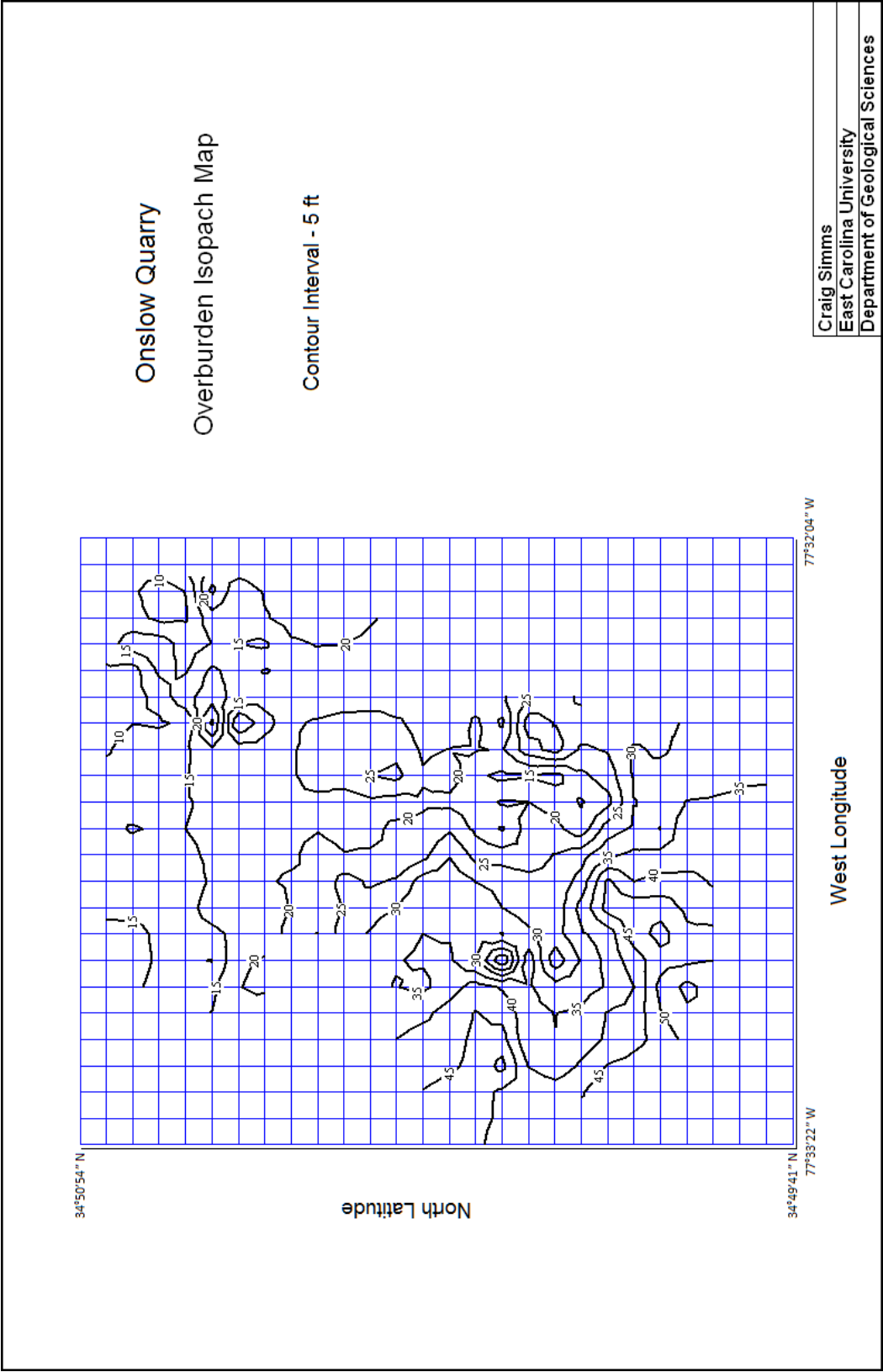


Figure 24 – Overburden Isopach Map from Borehole Data

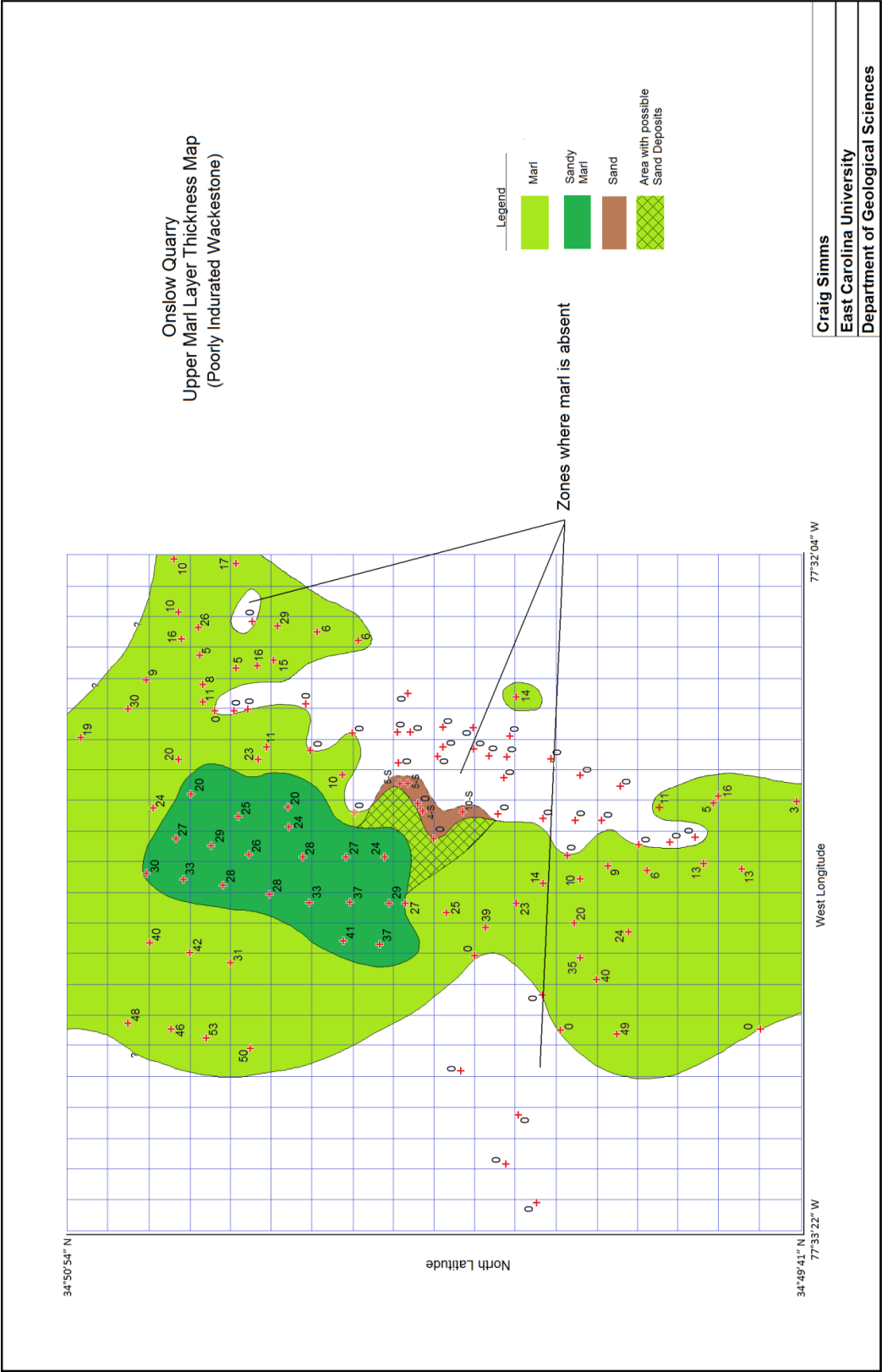


Figure 25 – Upper Marl Layer Thickness Map

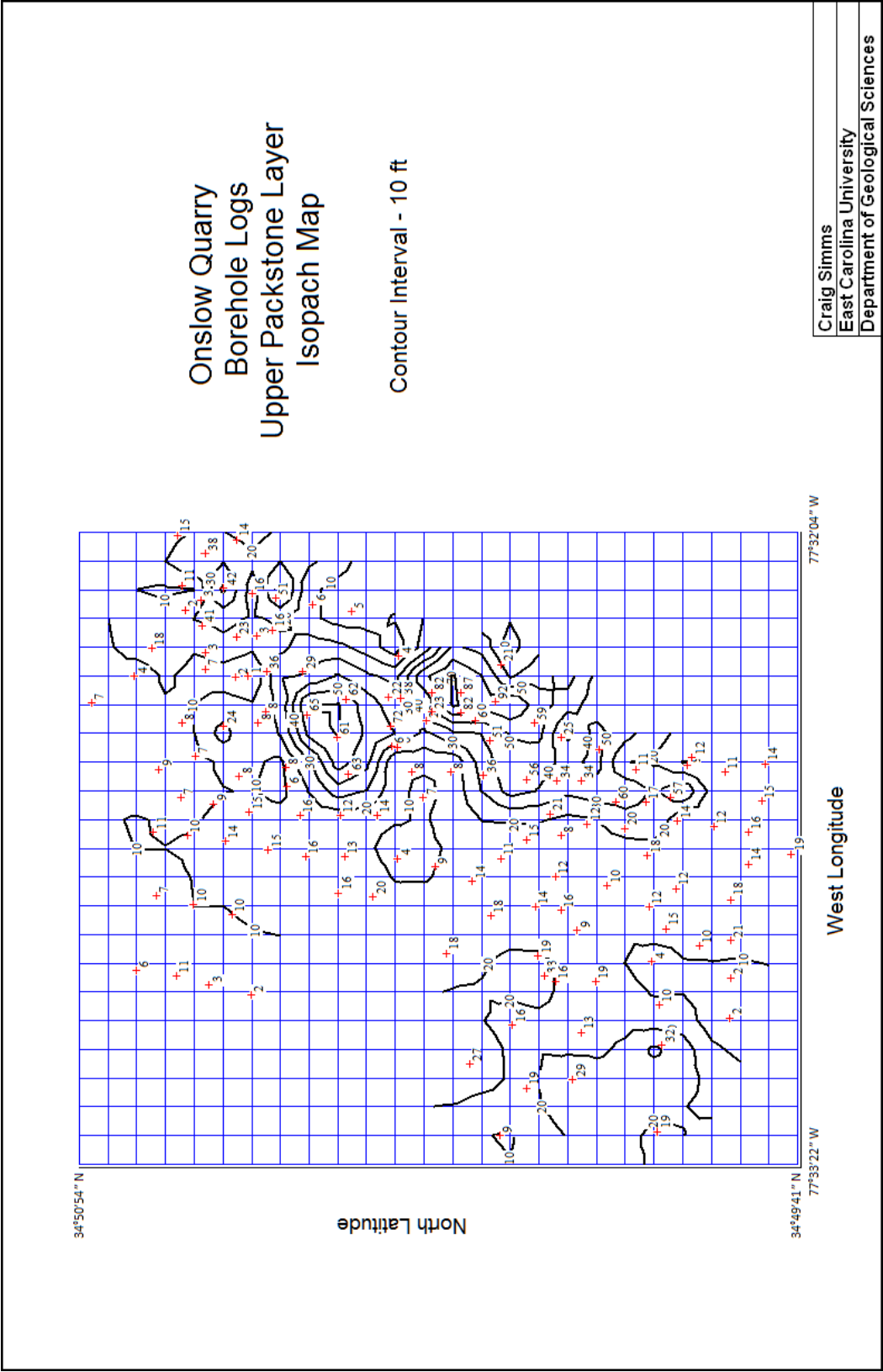


Figure 26 – Upper Packstone Layer Isopach Map

USGS Cross Section

The cross section (Fig. 27) created using well data from Brown, et al, (1972) and Seefelt, et al, (2009), displays the Cretaceous, Eocene and Oligocene age deposits from north to south across Onslow County; the Dixon core also reports Paleocene deposits. The cores show that the Eocene and Oligocene deposits are deeper in the south than they are in the north. Well core NC-ON-T-27 is located approximately 1.2 miles south-southeast of the quarry. This core reported 80 feet of Eocene shell limestone and 16 feet of Oligocene sandy/shell limestone. Also reported in the core was approximately 15 feet of post-Miocene shale and approximately 15 feet of fine sand.

The total depth of Eocene limestone reported in core NC-ON-T-27 coincides closely with the maximum observed depth of the limestone at the Onslow Quarry. This correlation provides evidence that the quarry operation is nearing the base of the Castle Hayne Formation, below which is the Cretaceous Peedee Formation.

Site Geologic Column

A geologic column was constructed using the Dunham classifications for the field samples; this column is depicted on Fig. 29. The observed occurrence of the carbonate sand layers was added to the column.

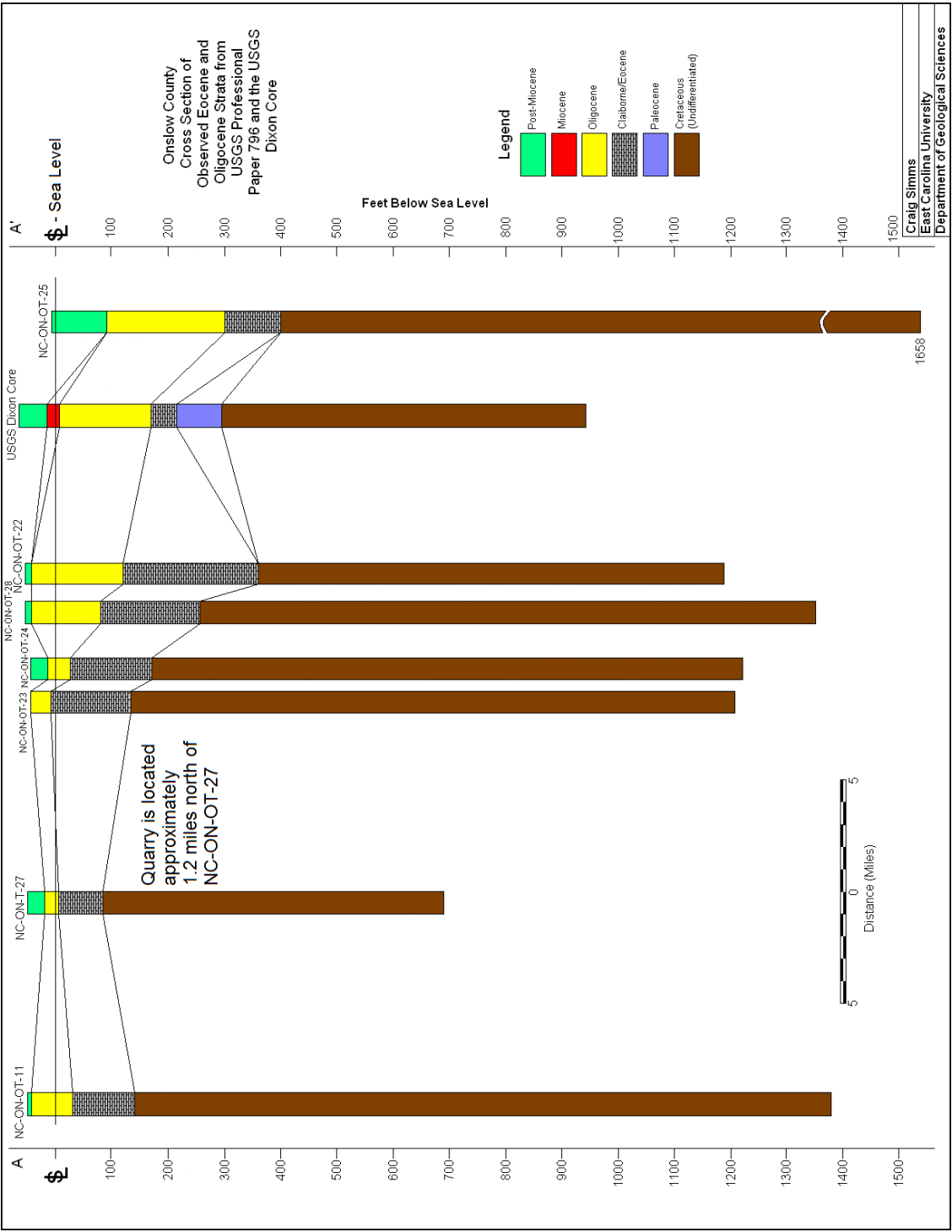
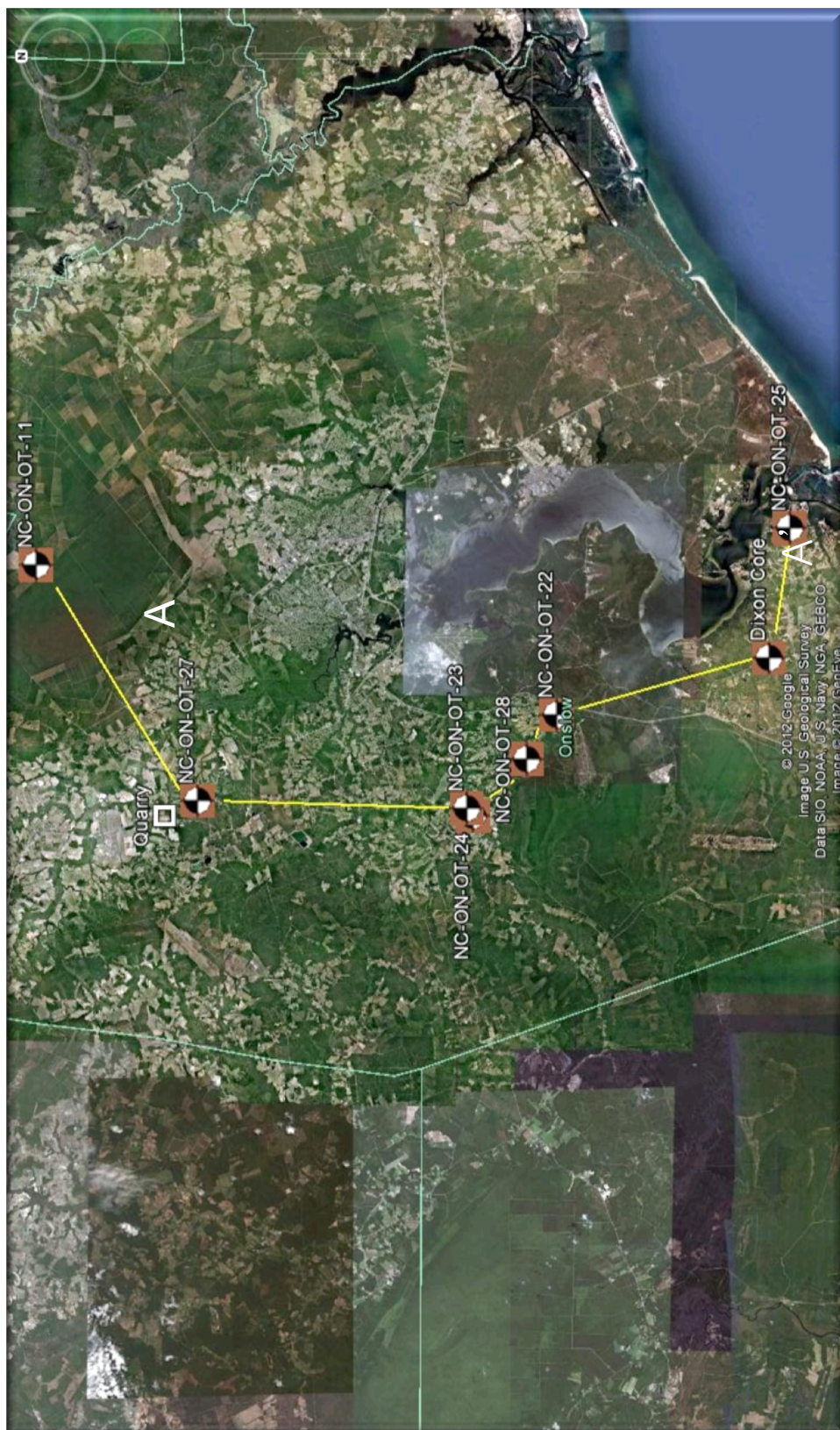


Figure 27 – Cross Section of the Eocene/Claiborne and Oligocene Sequences in Onslow County



**Figure 28 – Map of USGS and Dixon Core Wells and Quarry
Location in Onslow County**

Onslow Quarry Geologic Column

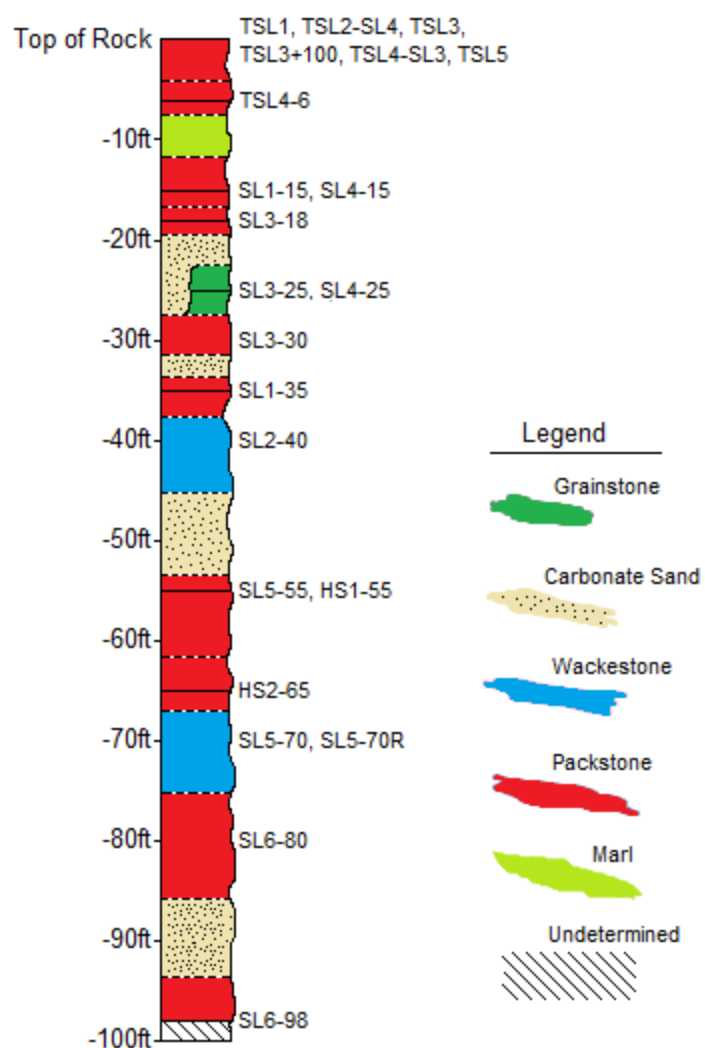


Figure 29 – Onslow Quarry Geologic Column and Samples at Depth

Stratigraphic Framework

Using the geologic section (Fig. 6a) and the site geologic column (Fig. 29) a stratigraphic framework can be constructed for the quarry. The three primary depositional units are the upper packstone, poorly indurated wackestone (marl) and lower limestone. The limestone layers of the lower unit have been designated as either a packstone or wackestone with a numeric suffix and the carbonate sand layers have been given a numeric suffix. Eleven layers were identified and designated in the lower unit. A geologic section was created using the Dunham classifications (Fig. 30) and with the designated units and layers added (Fig. 31). By comparing the layers on Fig. 30 with the layers on the geologic column (Fig. 31) and using the Folk and Dunham classifications, the characteristics of the limestone layers can be described and extrapolated.

Geologic Section of the Southeast Corner of the North Quarry with Unit and Layer Designations

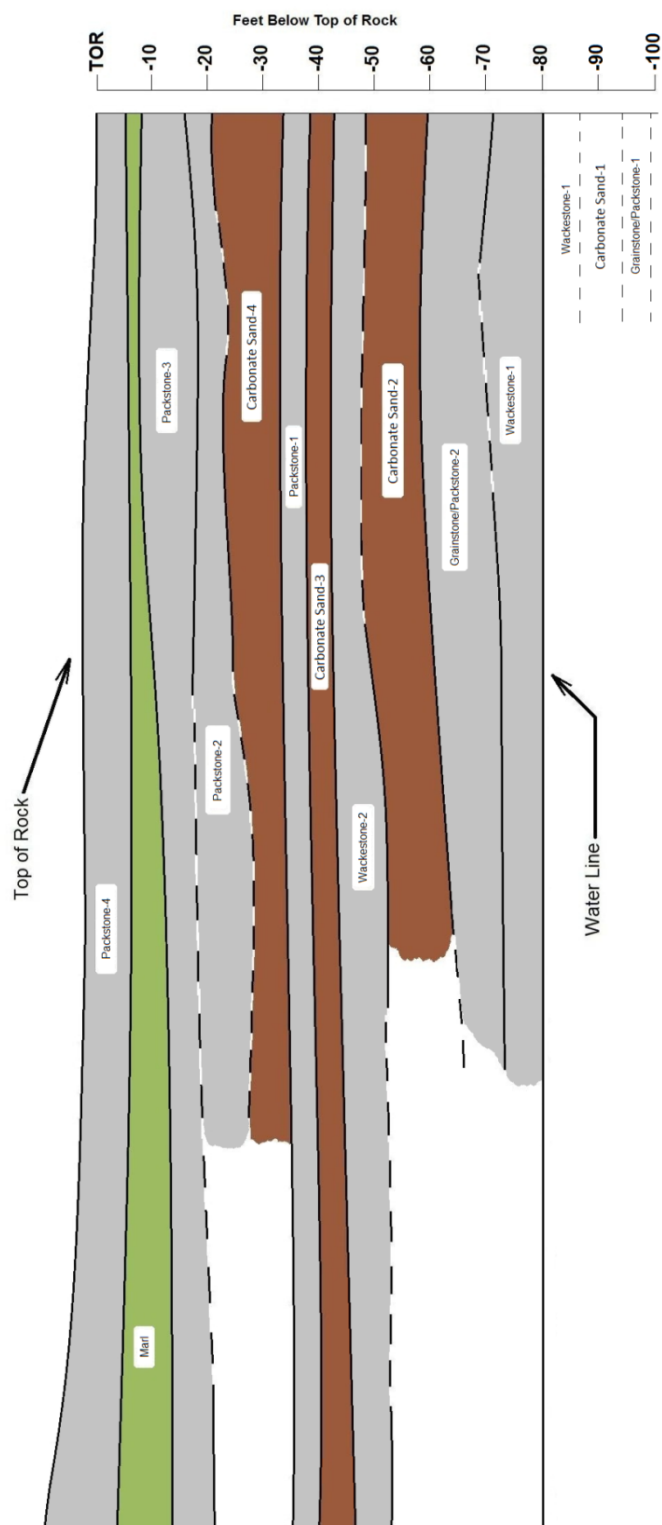


Figure 30 – Geologic Section with Unit and Layer Designations

Onslow Quarry Geologic Column

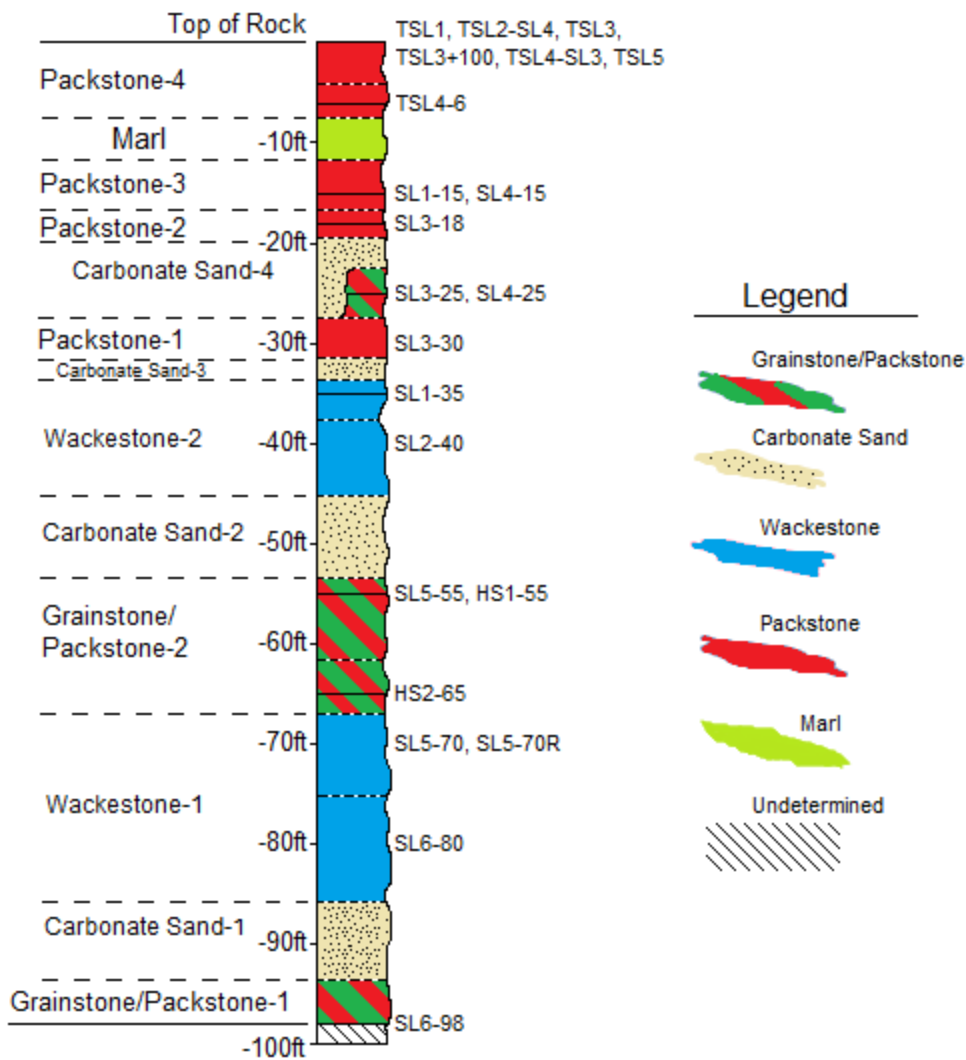


Figure 31 – Quarry Geologic Column with Unit and Layer Designations

Lithologic Descriptions

Wackestones

The wackestones are light to medium gray, well-cemented biomicrudites and biosparrudites. The transition in both wackestone layers to packstones is gradual. The beds range from less than three feet to approximately fifteen feet thick. Contacts occur most commonly where a wackestone layer contacts a carbonate sand layer; contacts with packstone layers are less well defined. Fossils include bryozoans, bivalves, echinoderms, foraminifera and gastropods. Intraclasts and some unidentified bioclasts are also present. The bioclasts are sub-angular to well-rounded and some exhibit micrite envelopes. The intraclasts are all well-rounded, indicative of extensive transport prior to deposition. Bivalves and bryozoans range in size to 20mm with echinoderm parts to approximately 5mm. Foraminifera are sub-millimeter in size. Detrital quartz and glauconite are present as is authigenic pyrite, which is found mainly in and near bryozoans. The quartz is sub-angular to well-rounded and up to approximately 2mm in size. The glauconite is oval in shape suggesting that it is fecal in origin; these pellets are sub-millimeter in size. Depositional features include trough cross-bedding and layering of bioclasts. The cross-bedded units are up to three feet in thickness. Bioclast layering is often seen concentrated near bedding planes. Porosity ranges from 6% to almost 18%. The voids are mostly less than 3mm in size. Diagenetic cements include granular and dog-tooth spar. Other diagenetic features include aggrading neomorphism of micrite to microspar and spar, dissolution of bivalve shells, filling of molds and dissolution of matrix. Table 5 displays the statistical data for the wackestone samples.

Sample Fossil	SL5-70 %	SL6-80 %	SL1-35 %	SL2-40 %	Minimum %	Maximum %	Average %
Bryozoans	9.4	14.9	11.2	11.8	9.4	14.9	11.8
Bivalves	3.1	6.0	4.0	2.2	2.2	6.0	3.8
Echinoderms	4.4	8.0	11.2	9.7	4.4	11.2	8.3
Gastropods	1.7	1.0	2.6	0.5	0.5	2.6	1.5
Quartz	4.6	14.2	2.8	1.2	1.2	14.2	5.7
Glauconite	4.0	1.7	1.4	0.7	0.7	1.7	2.0
Void Space	6.0	8.7	17.9	16.4	6.0	17.9	12.3
Matrix	56.8	38.1	41.5	52.2	38.1	56.8	47.2
Foraminifera	2.9	0.2	0.7	0.5	0.2	2.9	1.1
Other Intraclasts	5.2	3.1	4.2	1.9	1.9	5.2	3.6
U/I Intraclasts	2.1	4.1	2.6	2.9	2.1	4.1	2.9

Table 5 – Wackestone Statistical Data

Packstones

The packstones range in color from light to medium gray in the lower packstones to light gray/light brown/reddish-brown in the upper packstone sequence. They are well-cemented with a micritic matrix. The beds range in thickness from about five feet to ten feet. Contacts occur between the upper packstone and poorly indurated wackestone (marl), packstone-3 and the marl, packstone-2 and carbonate sand-4, packstone-1 and carbonate sand-4, packstone-1 and carbonate sand-3 and grainstone/packstone-2 and carbonate sand-2. The contacts between packstone-2 and packstone-3 and between wackestone-1 and grainstone/packstone-2 are less well defined, being more gradational. Fossil types include bryozoans, bivalves, echinoderms, gastropods and foraminifera with the most prevalent being bryozoans. A few coral fragments are also seen in the upper packstone. Also present are unidentified bioclasts and other intraclasts. The upper end of the size range for the bioclasts is higher than in the wackestones; bryozoan parts range in size to 30mm, echinoderms to 40mm, bivalves to 40mm and gastropods to 10mm. As with the wackestones, the foraminifera are sub-millimeter in size. The bioclasts other than the foraminifera are

sub-angular to well-rounded with some showing fracturing from deposition and compaction. Depositional quartz and glauconite are also evident; the quartz is sub-rounded to well-rounded and the glauconite is seen as oval shaped pellets. The quartz grains are sub-millimeter to 2mm in size and the glauconite pellets are sub-millimeter. Layering of bioclasts is evident in several of the layers and is most common near bedding planes. Porosity ranges from approximately 6% to almost 35%; the void spaces range in size from 1mm to 10mm. Quartz/phosphate dark nodules are evident in several layers. They are most commonly seen in the upper packstone where they range in size to 40mm. Diagenetic features include micrite envelopes, which were observed mainly in the sequences below the marl. Also observed were replacement of shells and skeletons by micrite and microspar, authigenic pyrite growths near bryozoans and some glauconite pellets, aggrading neomorphism of micrite to microspar and spar, dissolution of bivalve shells, filling of molds, and dissolution of matrix. Cements include dogtooth and granular spar. The statistical data for the packstones is included as Table 6.

Sample	SL1-15		SL4-15		SL3-18		SL3-30		SL4-25		TSL1		TSL2-SL4		TSL3		TSL3+100		TSL4-SL3		TSL4-6		TSL5		Min.		Max.		Avg.	
	Fossil	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Bryozoans Bivalves		21.5	9.6	10.2	14.5	17.7	12.7	11.2	3.6	5.7	11.6	7.6	22.9	3.6	22.9	12.4														
		6.3	2.9	1.0	3.7	3.1	0.0	3.6	0.6	0.4	1.2	0.8	5.4	0.0	6.3	2.4														
Echinoderms		7.6	15.9	14.0	9.1	8.1	13.4	11.2	4.9	2.5	7.5	1.0	2.7	1.0	15.9	8.2														
Gastropods		3.9	2.1	1.3	0.7	0.7	1.2	2.1	0.4	1.9	3.7	1.2	3.4	0.7	3.9	1.9														
Quartz		1.5	4.6	2.7	0.7	2.2	0.7	3.9	3.3	6.0	2.7	0.2	1.4	0.2	6.0	2.5														
Glauconite		0.2	2.1	1.5	1.6	1.7	3.4	3.7	5.2	5.3	2.1	0.4	0.4	0.2	5.3	2.3														
Void Space		6.3	9.2	20.0	7.0	17.9	34.6	8.5	10.5	9.4	12.6	11.3	14.5	6.3	34.6	13.5														
Matrix		46.3	42.2	36.5	51.8	41.0	28.0	49.9	52.9	53.9	50.9	69.6	45.2	28.0	69.6	47.4														
Foraminifera		0.2	0.6	0.6	0.5	1.1	0.2	2.5	7.7	7.2	0.8	4.5	1.1	0.2	7.7	2.3														
Other Intracasts		3.5	2.5	2.7	2.8	0.4	1.5	1.6	1.5	0.2	0.4	0.6	0.2	0.2	3.5	1.5														
U/I Bioclasts		2.6	8.4	9.4	7.5	6.1	4.1	1.8	9.5	7.6	6.6	2.7	2.9	1.8	9.5	5.8														

Table 6 – Packstone Statistical Data

Grainstone/Packstones

The grainstone/packstones show a transition from layers that closely resemble grainstones to those resembling packstones. They are medium gray to light gray/light brown and well cemented. The beds are approximately 5 and 15 feet thick. Abrupt contacts occur between grainstone/packstone-1 and carbonate sand-1 and grainstone/packstone-2 and carbonate sand-2. These beds contain bryozoans, echinoderms, gastropods, bivalves and very low numbers of foraminifera. Detrital quartz and glauconite are also present. Bioclasts and quartz grains are sub-angular to well-rounded; the glauconite is present as oval pellets. The largest bioclasts are bivalves and bryozoans to 20mm with gastropods and echinoderms to 5mm and foraminifera are sub-millimeter in size. Quartz grains are 2mm in diameter and the glauconite pellets are in the sub-millimeter range. Porosity ranges from 19% to 35% and the void spaces range to 3mm. A few quartz/phosphate dark nodules are present to 2mm. Diagenesis includes micrite envelopes, replacement of shells and skeletons by micrite and microspar, authigenic pyrite in and near bryozoans, aggrading neomorphism of micrite to microspar and spar, dissolution cavities of bivalve shells, filling of molds and dissolution of matrix. Cements include dogtooth and granular spar. The statistical data for the grainstone/packstones are included as Table 7.

Sample Fossil	SL5-55 %	HS1-55 %	SL6-98 %	Minimum %	Maximum %	Average %
Bryozoans	9.8	20.8	5.9	5.9	20.8	12.2
Bivalves	1.4	2.3	0.0	0.0	2.3	1.2
Echinoderms	10.3	2.1	2.7	2.1	10.3	5.0
Gastropods	3.0	4.9	0.4	0.4	4.9	2.8
Quartz	8.7	4.2	22.0	4.2	22.0	11.6
Glauconite	2.1	1.3	2.5	1.3	2.5	2.0
Void Space	27.9	19.7	35.4	19.7	35.4	27.7
Matrix	26.1	40.3	26.4	26.1	40.3	30.9
Foraminifera	0.7	0.2	0.6	0.2	0.7	0.5
Other Intraclasts	4.1	1.1	2.7	1.1	4.1	2.6
U/I Intraclasts	5.9	3.2	1.5	1.5	5.9	3.5

Table 7 – Grainstone/Packstone Statistical Data

Diagenetic Features

Diagenetic features evident in the thin sections range from early pre-lithification features such as micrite envelopes to late features such as matrix dissolution, and dogtooth and granular spar linings. A description of each follows.

Micrite Envelopes

Envelopes or thin layers of micrite formed by microboring of the host grain by cyanobacteria (Flügel, 2004) are a common feature in many of the thin sections. They occur mostly on bivalves and gastropods; the envelopes vary in thickness but are all sub-millimeter size. Fig. 32 depicts an envelope surrounding a gastropod mold. The original shell material was subsequently dissolved but the envelope remains. This sample is from thin section SL5-55.

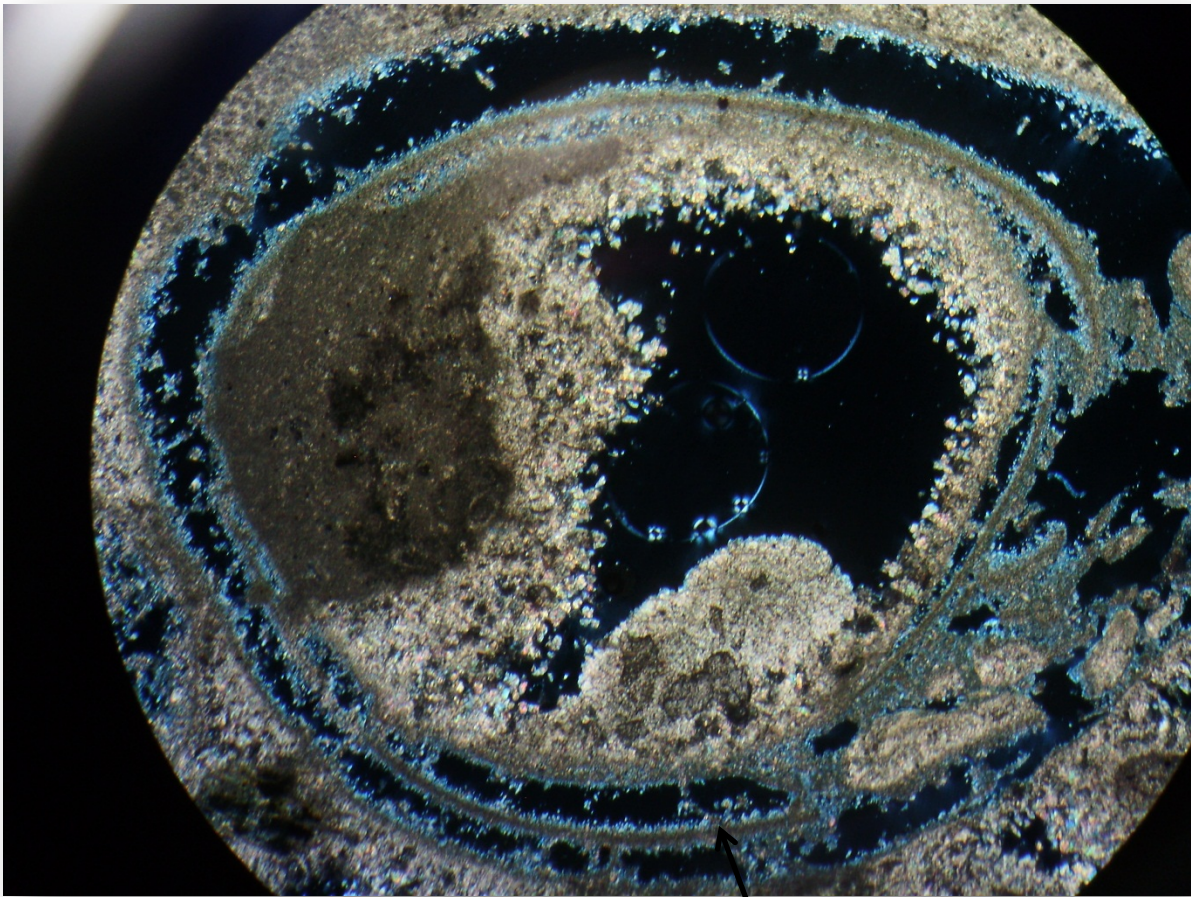


Figure 32 – Micrite Envelope Surrounding a Gastropod

Micrite Envelope

Authigenic Pyrite

Pyrite is seen in all thin sections except SL6-98. It is found primarily in and near bryozoan skeletons where organic matter was more abundant at the time of deposition. It is also seen occasionally surrounding glauconite pellets and in the matrix as disseminated mineral grains. Fig. 33 shows pyrite in bryozoan skeletons.

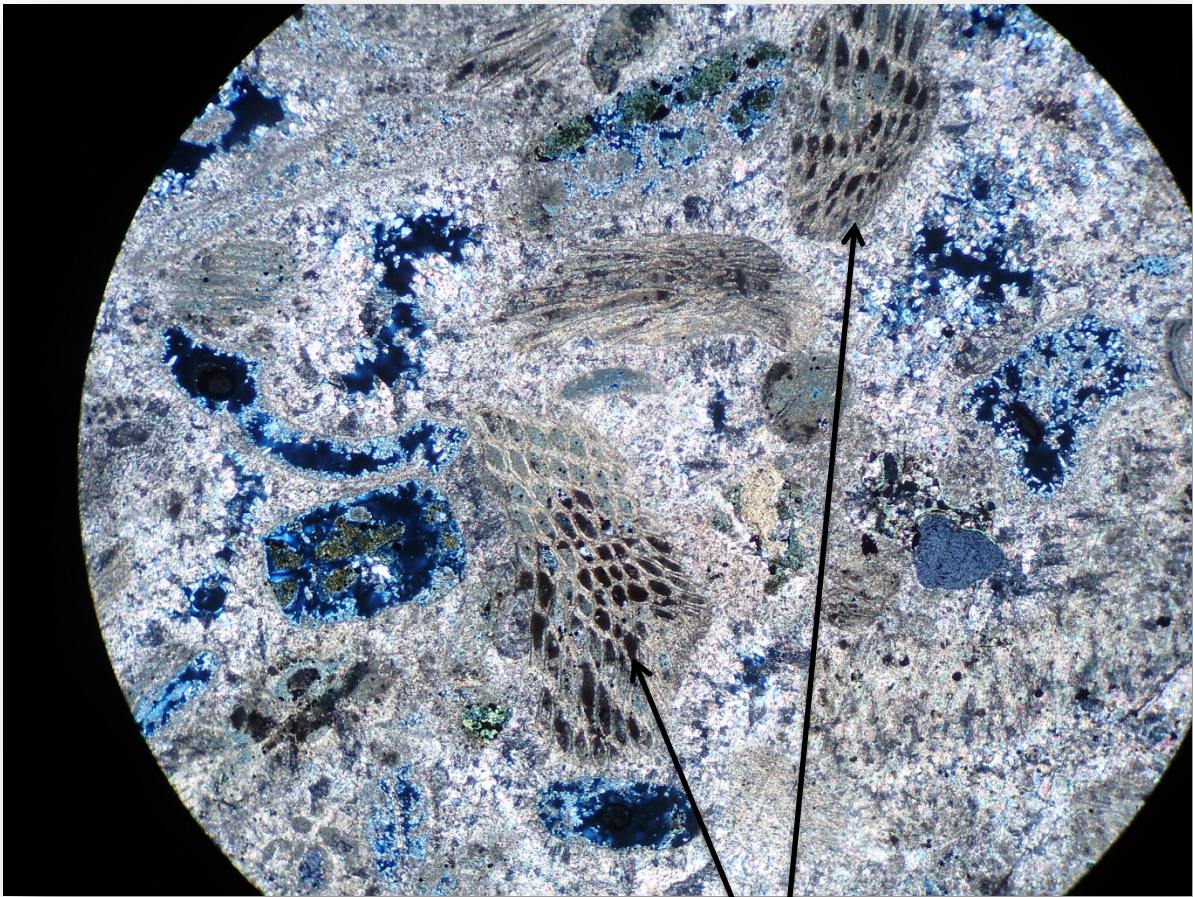


Figure 33 – Authigenic Pyrite in Bryozoan Skeletons

Authigenic Pyrite

Shell Dissolution

Two forms of shell dissolution were seen in the thin sections. The first shows the dissolution of bivalves and some gastropod shells after lithification resulting in moldic structures. The second is the dissolution of original echinoderm and bryozoan skeletons as a late diagenetic feature. The second form is much less common because the calcitic skeletons of the bryozoans and echinoderms are more resistant to dissolution than the aragonitic bivalve and gastropod shells. Fig. 34 displays the dissolution of a bivalve shell resulting in a mold.

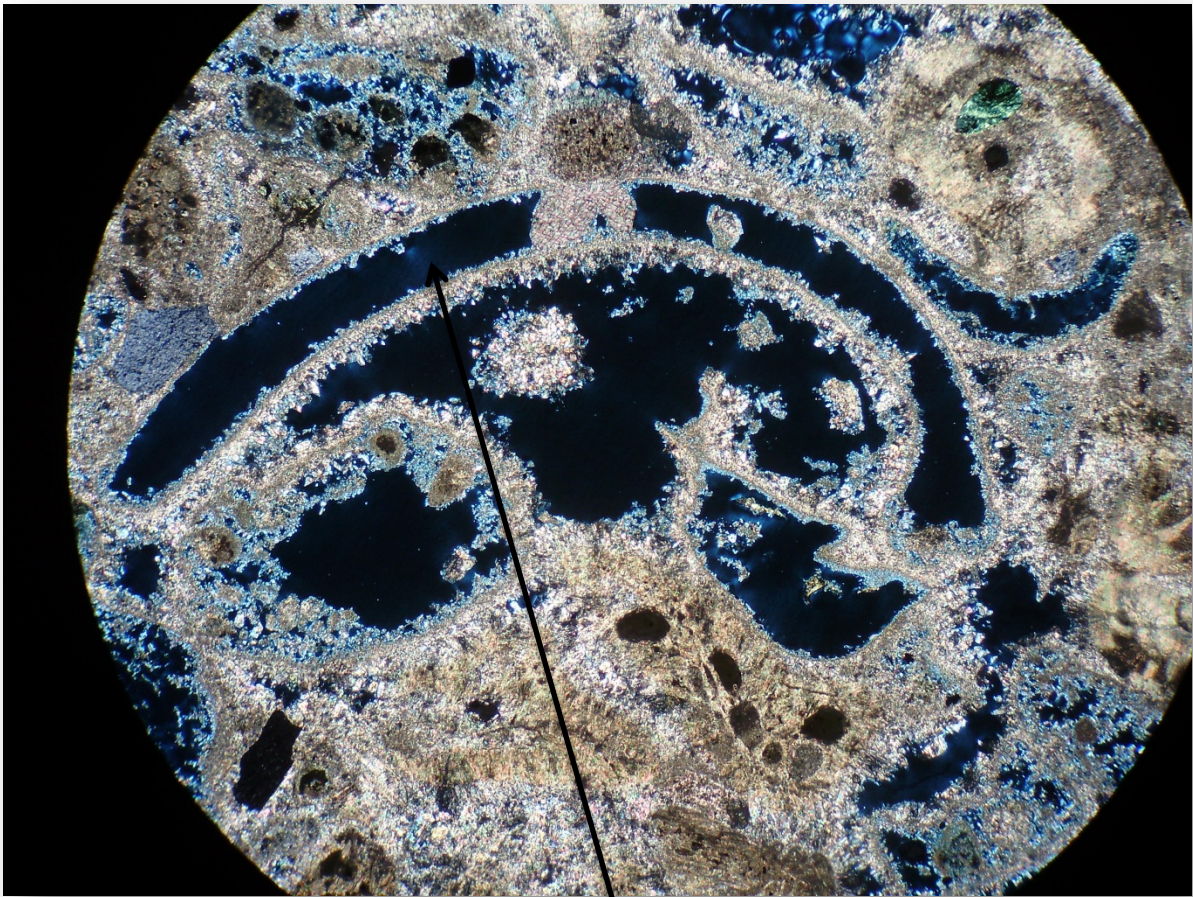


Figure 34 – Dissolution of Bivalve Shell

Dissolved Bivalve Shell

Shell/Skeleton Replacement

Replacement by micrite and microspar is seen in bryozoans, gastropods and echinoderms. There was some replacement in bivalves and in the few coral fragments. Fig. 35 shows an example of shell replacement in a gastropod shell and a bryozoan skeleton.

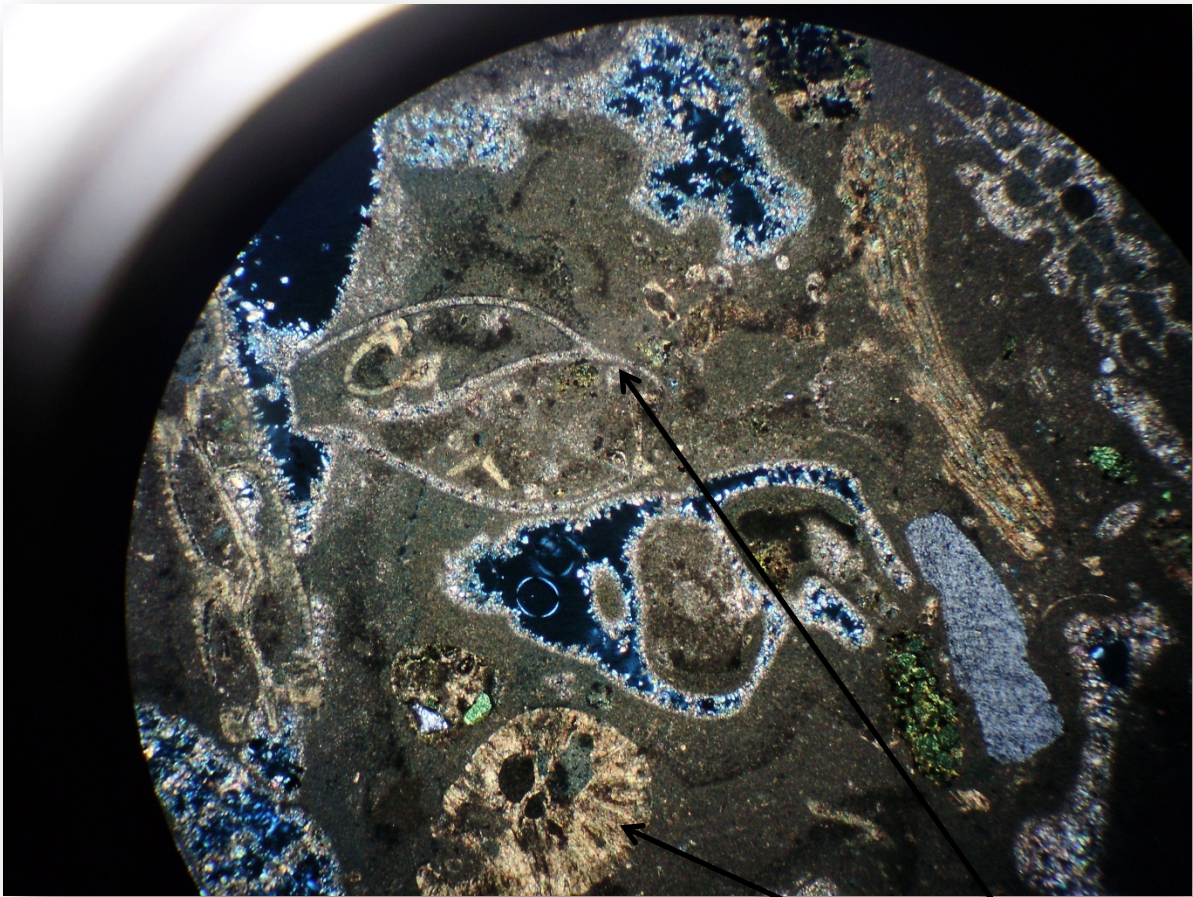


Figure 35 – Replacement in a Bryozoan Skeleton and Gastropod Shell

Gastropod
Bryozoan

Neomorphism

Both aggrading and degrading neomorphism were observed in the thin sections, primarily of the matrix. The aggrading form is more common. An example of aggrading neomorphism is shown on Fig. 36.

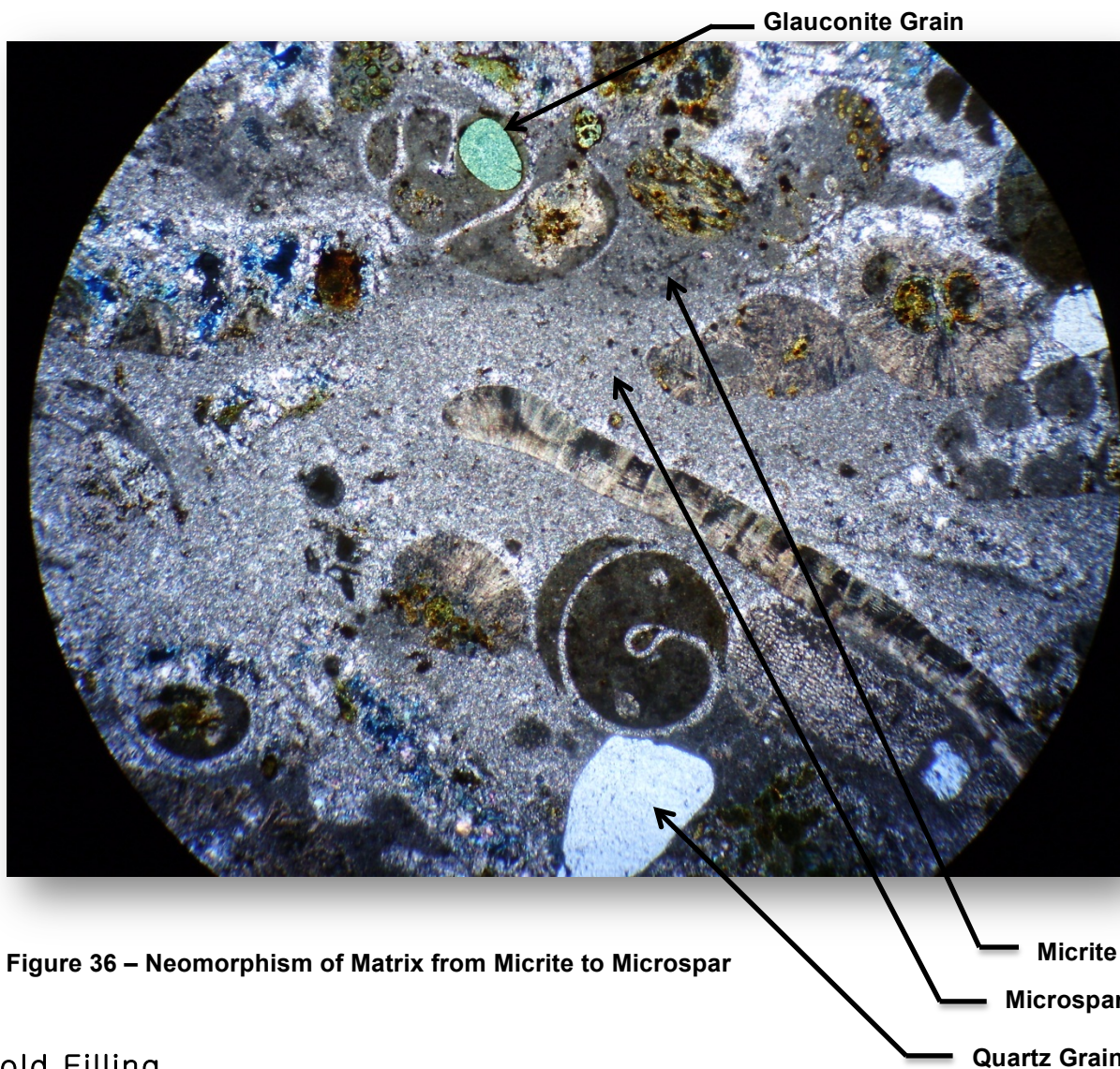


Figure 36 – Neomorphism of Matrix from Micrite to Microspar

Mold Filling

After early stage bivalve and gastropod shell dissolution many of the resulting molds have been filled with either micrite or microspar. Many molds are incompletely filled and lined with granular and/or dogtooth spar. These features are seen in many of the samples and are shown on Fig. 37.

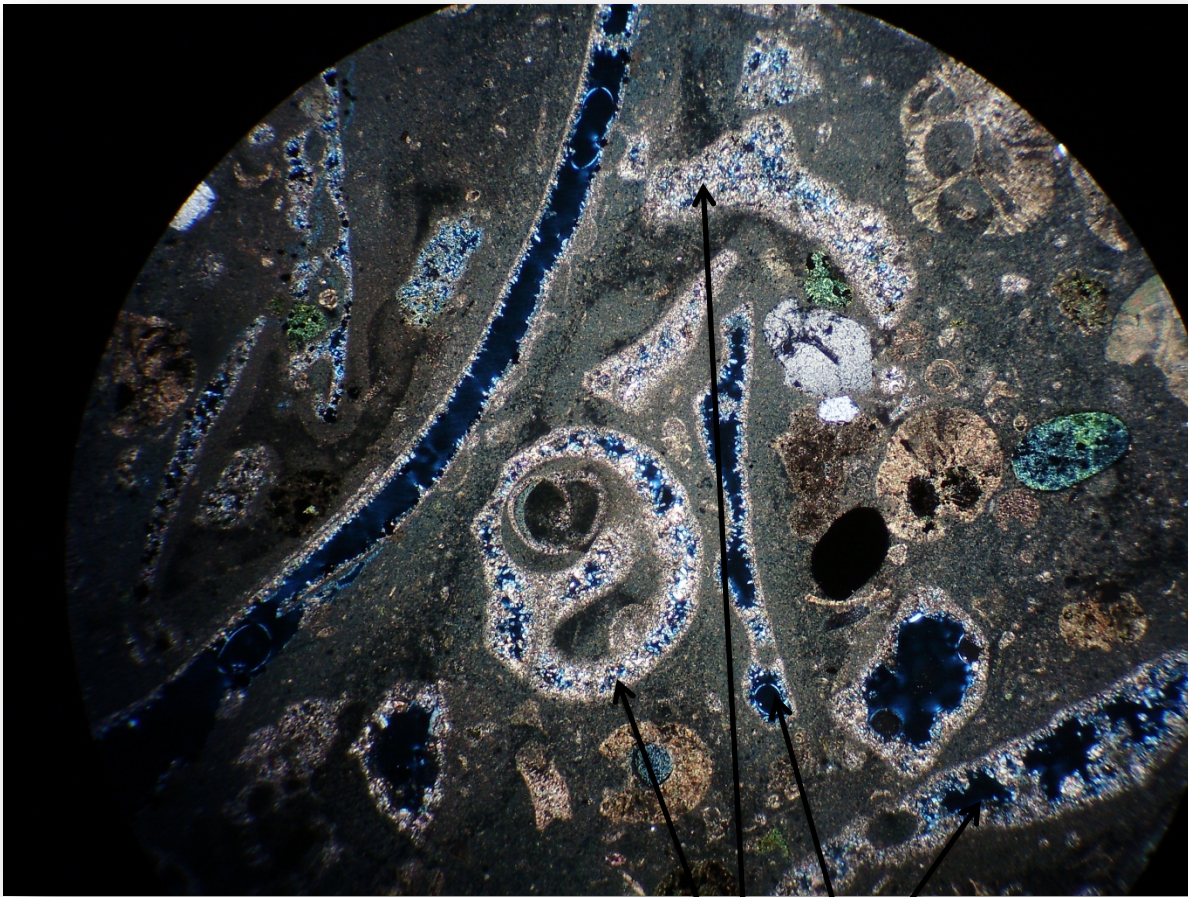


Figure 37 – Complete and Incomplete Mold Fillings

Incomplete Mold Fillings

Complete Mold Fillings

Cements

The primary cements present in thin section are granular and dogtooth spar. They are common as linings in molds and around echinoderms and bryozoans. There are also occurrences of radiating spar. Fig. 38 shows examples of granular and dogtooth spar.

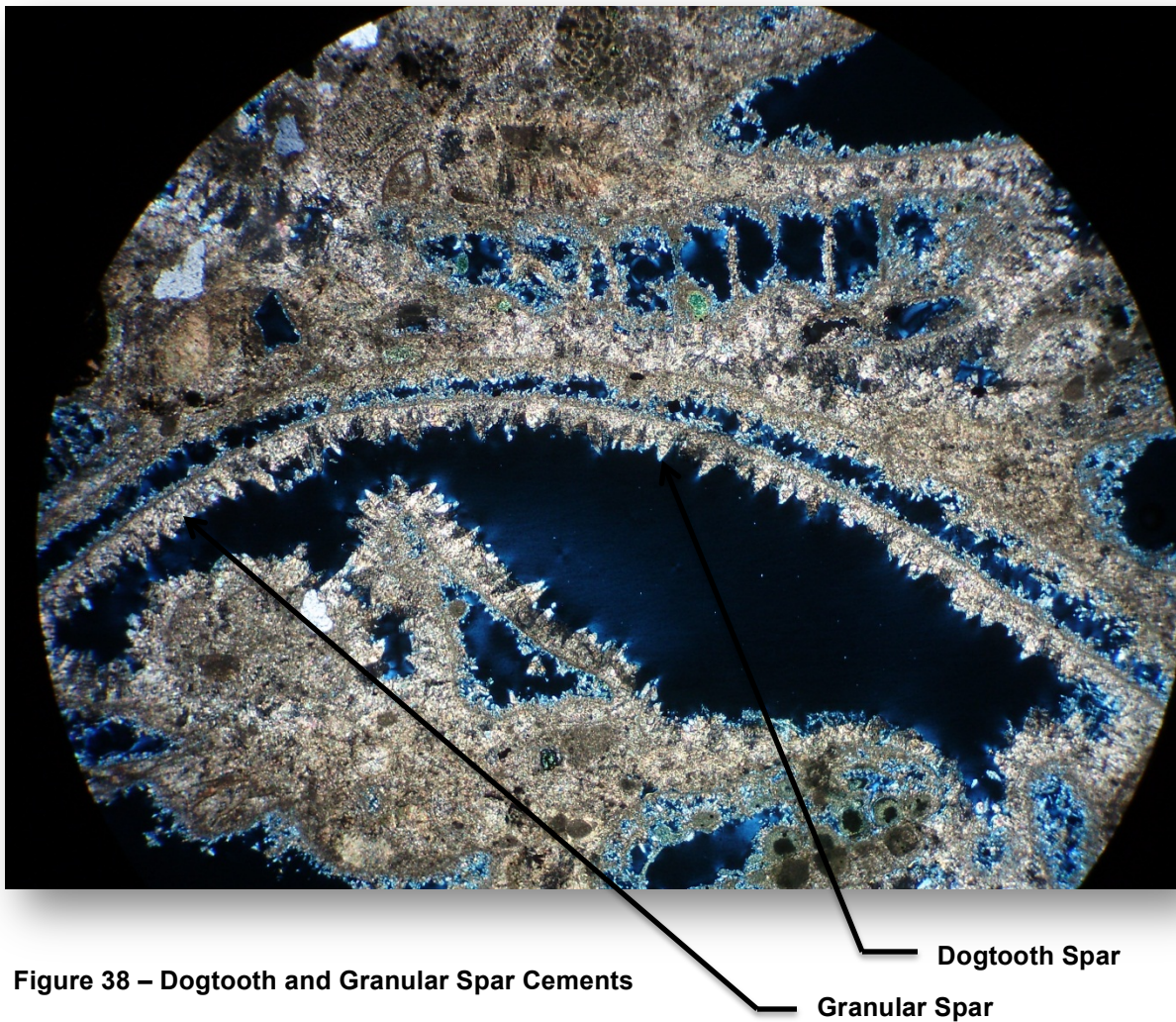


Figure 38 – Dogtooth and Granular Spar Cements

Porosity

Several types of porosity evident in the thin sections include intraparticle, intercrystal, moldic and vug. These are thought to be secondary in origin. The intraparticle porosity is likely due to dissolution of bivalve and gastropod shells during the early post-lithification stage and dissolution of shells, skeletons and fabric during later stage diagenesis. Intercrystalline porosity is considered to be primarily caused by incomplete crystal growth during mold filling. Intraparticle and intercrystal porosities are shown on Fig. 38. Much of the porosity is moldic porosity resulting from the dissolution

of bivalve and gastropod shells. Moldic porosity is evident on Fig. 34. Vug type porosity (Fig. 39) is more evident in samples from greater depth but this is not a strict rule.

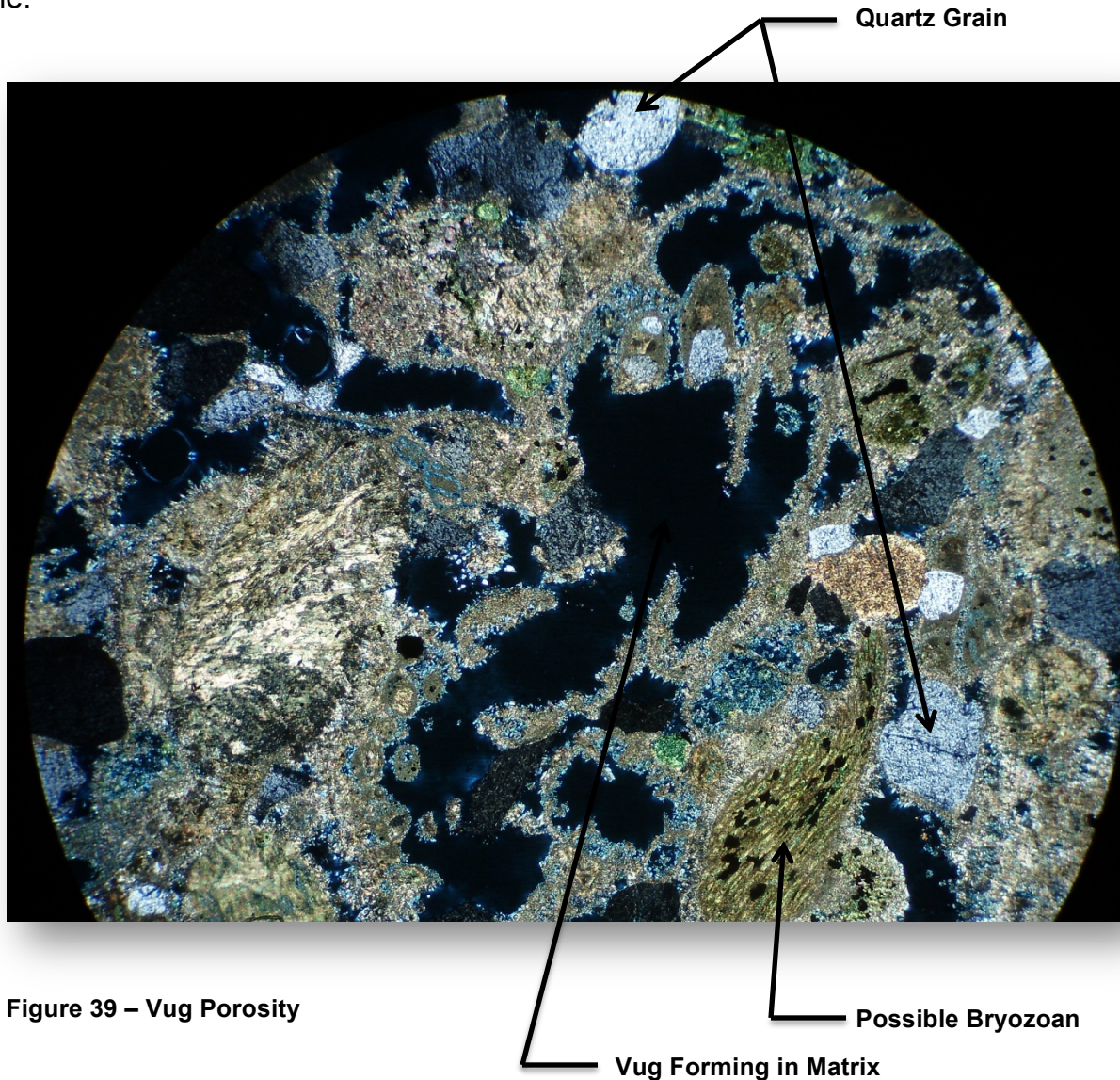


Figure 39 – Vug Porosity

Lithologic and Diagenetic Trends

Examination of the thin sections indicated most samples were originally lithified lime mud. Early spar cementation may have affected the grainstone/packstones. Each sample also shows damage to bioclasts during deposition and possibly by burial compaction. The percentage of micrite (Chart 1) generally decreases with increasing

depth as evidenced by the trend line. The highest percentage of micrite, 69.6%, is seen in TSL4-6 which is 6 feet below the top of rock. The second highest percentage, 56.8% is in SL5-70. This sample is among the least porous of the samples even though it was collected 70 feet below the top of rock. The deepest sample, SL6-98, displayed the second lowest micrite percentage: 26.4%.

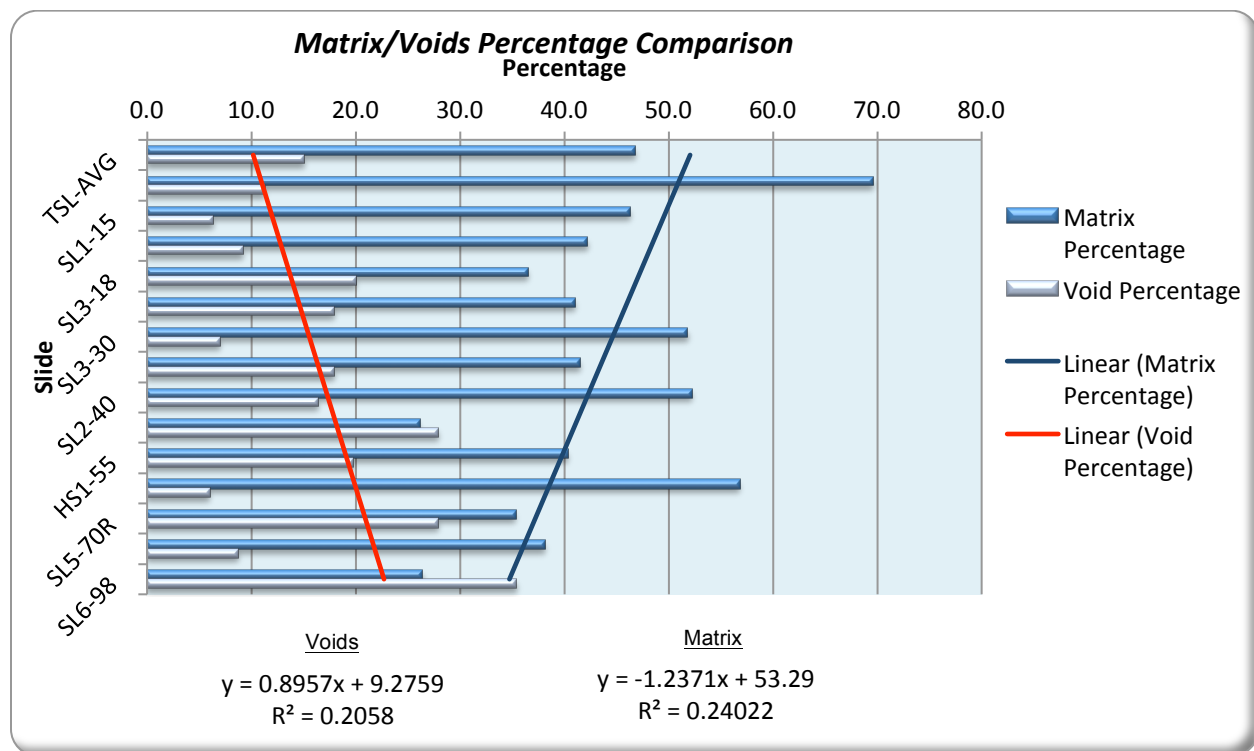


Chart 1 – Matrix to Voids Point Count Percentage Comparison

In direct contrast to the decreasing percentage of micrite with increasing depth, the percentage of void spaces increases with increasing depth (Chart D2). The relationship between the matrix and void percentages is shown on Chart 1. The trend line for void spaces shows that the percentage of voids more than doubles, from 10% to over 20%, from the top of rock to the deepest sampling location. The linear percentage of matrix decreases from approximately 52% to approximately 38%. This trend does

have a greater slope than the void trend line. This difference is explained by the fact that many of the voids seen in the thin sections were originally bivalve and gastropod molds that have been enlarged beyond their original boundaries.

Echinoderms do not exceed 16% in the samples (Chart D3). The linear trend shows a decrease with increasing depth, likely due to dissolution. This trend is also the case for bryozoans (Chart D4), gastropods (Chart D6), foraminifera (Chart D7) and unidentified bioclasts (Chart D11). The slope of the trend line for gastropods, -0.004, is very minimal and indicates no significant change from top to bottom. The percent range for gastropods is 0.4 to 4.9%.

The other examined components, bivalves (Chart D5), quartz (Chart D8), glauconite (Chart D9) and other intraclasts (Chart D10) all show increasing percentages with depth. Of the components with increasing trends, only quartz shows a significant slope - 0.8911. The others, glauconite - 0.0545, bivalves - 0.0373 and other intraclasts - 0.095 show only a negligible slope with depth.

The quartz in the samples is below 5% in all but three of the samples, HS1-55 - 8.7%, SL6-80 - 14% and SL6-98 - 22%. Sample SL6-98 also has larger quartz grains than any of the other samples. No evidence exists that any of the quartz is authigenic. In all thin sections the quartz is sub-angular to rounded and none of the quartz grains have developed as replacive minerals from pre-existing carbonate crystals. The increase in abundance and size of the grains in sample SL6-98 is attributed to a higher energy environment.

Glauconite in the samples is mostly attributed to clay debris that has passed through the digestive tracts of burrowing organisms (Flügel, 2004) and was deposited on the sea floor. The rounded pellets are reflective of transport or their original shape.

Diagenesis – General Discussion

The increase or decrease of each component is reflective of the diagenetic regimes that affected the rocks. All were initially in a seafloor and shallow-marine subsurface regime. After compaction and lithification all but the topmost rock layer were buried under additional carbonate deposits. The topmost rock layer may have been buried as well by additional deposits, but if this is indeed the case, there has most certainly been some erosion resulting in a reduced thickness of the layer. The well consolidated layers originally were lithified with a micritic matrix. The carbonate sand layers do not contain micrite, as they were deposited along banks and shoals where the presence of lime mud would be unlikely. The lack of lithification suggests that the carbonate sands have stayed in the uppermost level of the eogenetic realm.

The lithified strata have gone through multiple diagenetic events. The thin sections show evidence of bivalve shell dissolution, dogtooth and granular spar cementation, replacement of original shell material with micrite and microspar, syntaxial overgrowths on echinoderms, dissolution of fabrics, neomorphism of fabrics, shell fragments and cements and authigenic growths of glauconite and pyrite.

Prior to lithification micrite envelopes formed around some of the bioclastic fragments creating cortoids. As compiled by Flügel (2004), micrite envelopes form in three ways: 1) destructive micritization related to microboring organisms, 2) constructive micrite envelopes related to epilithic organisms, and 3) partial dissolution and

recrystallization. No evidence of constructive micrite envelopes exists as no algae or cyanobacteria remains were noticed in the thin sections.

Early post-lithification diagenesis occurred in the shallow marine phreatic zone and includes dissolution of bivalve shells, other aragonitic and high-magnesian calcite shell forms and the replacement of original shell material with low-magnesian calcite. After dissolution of aragonite and high-magnesian calcite shell material, precipitation of dogtooth spar was followed by precipitation of granular spar along the linings of molds and other voids. In some cases the granular spar completely fills the void space, sharply reducing the local porosity. The development of syntaxial overgrowths around echinoderms and aggrading neomorphism of micrite and shell fragments to microspar and spar also occurred.

At some time, possibly in the late Eocene Epoch, conditions at the quarry location shifted from the marine phreatic zone to the meteoric zones that currently exist at the site. The present day water table is approximately 60 feet below sea level but has been artificially lowered by pumping to keep the water levels low enough for mining. The North Carolina Department of Environmental and Natural Resources (NCDENR) Division of Water Resources maintains six monitoring wells located approximately 0.15 miles south of the south quarry (NCDENR – DWR website, 2012). NCDENR-DWR has ground water level data for monitoring well W 26C4 from January, 2005 to January, 2012. During this timeframe, the water level in this well ranged from approximately 10 to 20 feet below sea level. The probability exists that since the shift to the meteoric diagenetic zones, the strata have been affected by vadose and phreatic zone diagenesis.

The vadose meteoric diagenetic zone is often very chemically aggressive due to acidic waters percolating down from the surface, undersaturation with respect to CaCO_3 and high dissolved CO_2 levels (Boggs, 2009). These conditions cause dissolution of aragonite, high-magnesian calcite and low-magnesian calcite, which creates vuggy fabrics in matrix, dissolution of shells and cements. The possibility also exists that low-magnesian calcite will precipitate if the pore waters become saturated with CaCO_3 .

The phreatic meteoric diagenetic zone is very similar to the vadose meteoric zone in that the pore waters are often very chemically aggressive. Dissolution is common and precipitation of low-magnesian calcite can also occur. The precipitation of authigenic minerals also occurs in this zone.

Depositional Sequences

The depositional environment for each unit can be interpreted using the microfacies zone assignments from Tables 8 and 9; the assignments follow after Flügel, 2004. The homoclinal carbonate ramp is the depositional model and a graphical facies model for the depositional environments designed after Flügel, 2004, was created (Fig. 41). This model is viewed as the most likely scenario for deposition. The individual units are shown in their approximate location on the ramp with arrows indicating the shifting direction of depositional depth. The sequences and their associated units are described below.

Sample	Microfacies	Microfacies Zone	Notes
SL6-98	RMF-27	Inner Ramp Shoal	
SL6-80	RMF-14	Inner Ramp Open Marine	
SL5-70	RMF-14	Inner Ramp Open Marine	
SL5-70R	RMF-27	Inner Ramp Shoal	
HS2-65	RMF-27	Inner Ramp Shoal	
SL5-55, HS1-55	RMF-27	Inner Ramp Shoal	
SL2-40	RMF-14	Inner Ramp Open Marine	
SL1-35	RMF-14	Inner Ramp Open Marine	
SL3-30	RMF-14	Inner Ramp Open Marine	
SL3-25, SL4-25	RMF-27	Inner Ramp Shoal	SL3-25 carbonate sand
SL3-18	RMF-27	Inner Ramp Shoal	
SL1-15, SL4-15	RMF-14	Inner Ramp Open Marine	
TSL1, TSL-SL4, TSL3, TSL3+100, TSL4-SL3, TSL4-SL6, TSL5	RMF-26/27	Inner Ramp Shoal	

Table 8 – Sample Microfacies Assignments

Unit	Microfacies Zone
Grainstone/Packstone-1	RMF-27
Carbonate Sand-1	RMF-27
Wackestone-1	RMF-14
Grainstone/Packstone-2	RMF-27
Carbonate Sand-2	RMF-27
Wackestone-2	RMF-14
Carbonate Sand-3	RMF-27
Packstone-1	RMF-26/27
Carbonate Sand-4	RMF-27
Packstone-2	RMF-26/27
Packstone-3	RMF-26/27
Marl	RMF-19
Packstone-4	RMF-26/27

Table 9 – Unit Microfacies Assignments

Homoclinal Ramp Facies Model - Inner Shoal Restricted

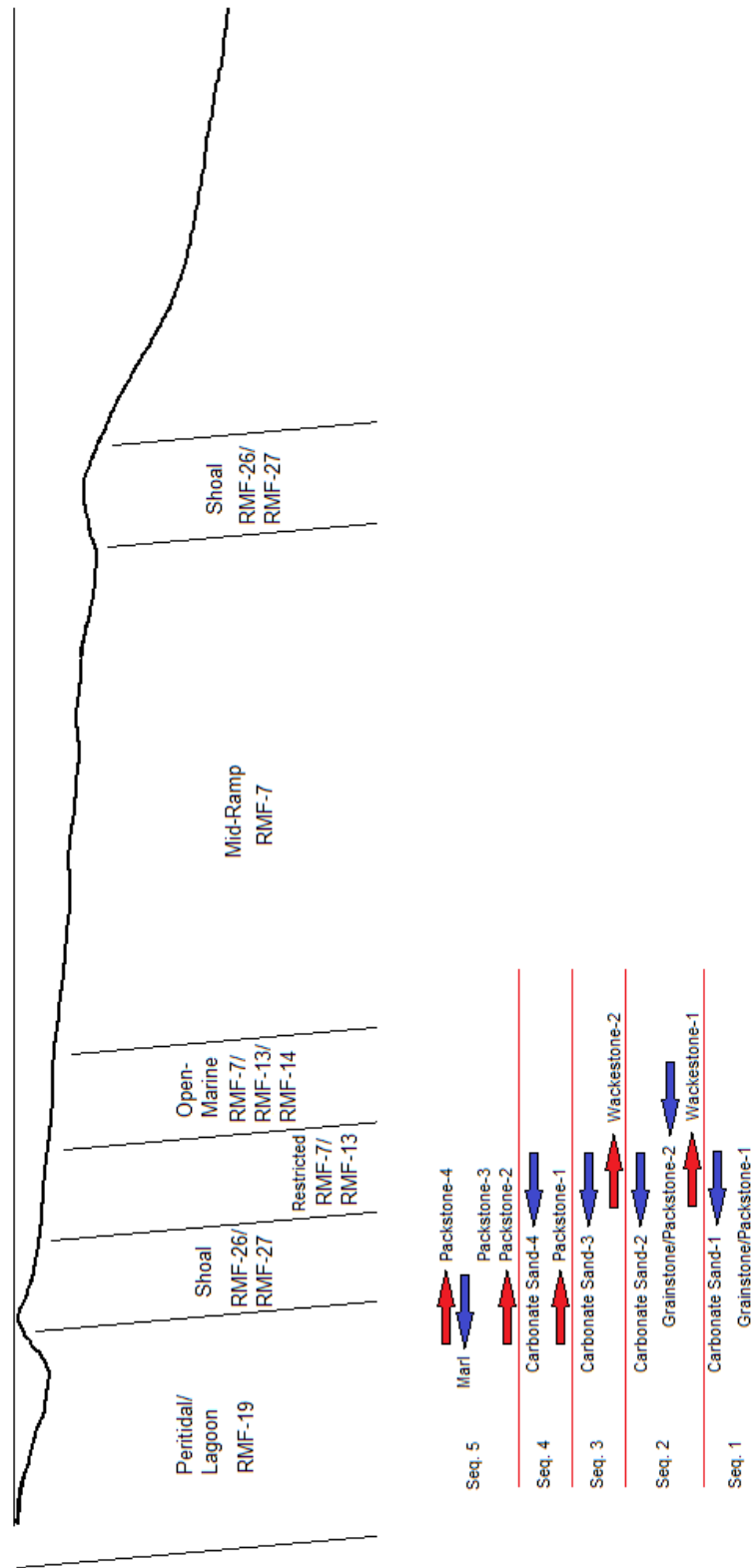


Figure 40 – Homoclinal Ramp Inner Shoal Depositional Facies Model – After Flügel, 2004

Sequence 1

Grainstone/Packstone-1: Deposition occurred in the inner ramp shoal microfacies zone (RMF-27) but it is unclear whether a depositional or erosional event immediately preceded this lowermost limestone unit.

Carbonate Sand-1: This unit is also in the inner ramp shoal microfacies zone but nearer to the shore where wave action reworked the bryozoan fragments. Little original biogenic material would have been deposited in this zone. Rather, most or all of the grains would have been carried in by wave action. This is the uppermost unit of the sequence.

Sequence 2

Wackestone-1: A flooding event created a deeper seawater environment which allowed for deposition of lime mud and resulted in a change from carbonate sand and biosparrodite of the two underlying units to a biomicrudite in the open marine microfacies zone (RMF-14).

Grainstone/Packstone-2: Shallowing occurred and shifted deposition back to RMF-27, the inner ramp shoal. Bryozoans are well worked in this unit; most fragments are less than 20mm in size. Wave action has created cross-bedded deposits.

Carbonate Sand-2: A further shallowing shifted deposition closer to shore in the inner ramp shoal. Wave action reworked the bryozoan and coral fragments thus creating well-rounded bioclasts.

Sequence 3

Wackestone-2: Water depths initially deepen at the base of this unit where the facies changed into the inner ramp restricted/open marine facies zone. More micrite was deposited in the lower section where wave action would have been less important than in the shallower facies zones. As accumulation continued the facies changed back to the inner ramp shoal zone.

Carbonate Sand-3: Sediment accumulation once again shifted deposition farther into the inner ramp shoal. Bryozoan and coral clasts are well-rounded from continual reworking by wave action.

Sequence 4

Packstone-1: This unit is still the inner ramp shoal zone but due to slightly deepened water the energy from wave action was lessened. Wave action created cross-bedded deposits.

Carbonate Sand-4: Either sediment accumulation or shifting of sediments moved the depositional environment slightly landward to the edge of the inner ramp shoal facies zone. Well-rounded bryozoan and coral fragments are abundant. A transition from the landward inner ramp shoal to the more seaward inner ramp shoal is evident.

Sequence 5

Packstone-2: The depositional environment remained in the inner ramp shoal facies zone but shifted slightly seaward. Sand dollars are first seen in this unit; this could indicate a transition in the biota of the environment.

Packstone-3: Flooding caused a transition to the inner ramp restricted/open marine zone (RMF-14). No sand dollars are seen, possibly due to the increased depth.

Poorly Indurated Wackestone (Marl): The sand/marl deposit and associated sand lens implies that the marl was possibly deposited in a lagoonal environment with the sand accumulating on an adjoining beach zone. The corresponding zone is RMF-19, the lagoonal facies zone. Quiet water deposition allowed for the preservation of larger bryozoan skeletons up to 40mm in length while sand accumulated along one edge forming a beachfront. The marl, sand/marl and sand deposits are surrounded by limestone; this implies a restricted depositional environment. This interpretation differs from Coffey (2000) who placed all Paleogene marl deposition in a deep shelf environment. Two possible separate and distinct marl depositional environments may be evident here and on the Coastal Plain of North Carolina.

Packstone-4: Shallowing of the sea caused a transition back to the inner ramp restricted/open marine facies zone. Cross-bedding is seen in this unit.

A representation of the relative sea water depths for the layers is shown on Chart 2. Depth is shown from shallowest – 1 to deepest – 5. Five relative sea level depths are inferred. After the deposition of the upper limestone unit, sea level apparently dropped, possibly due to uplift along the Cape Fear Arch (Ward, et al. 1978).

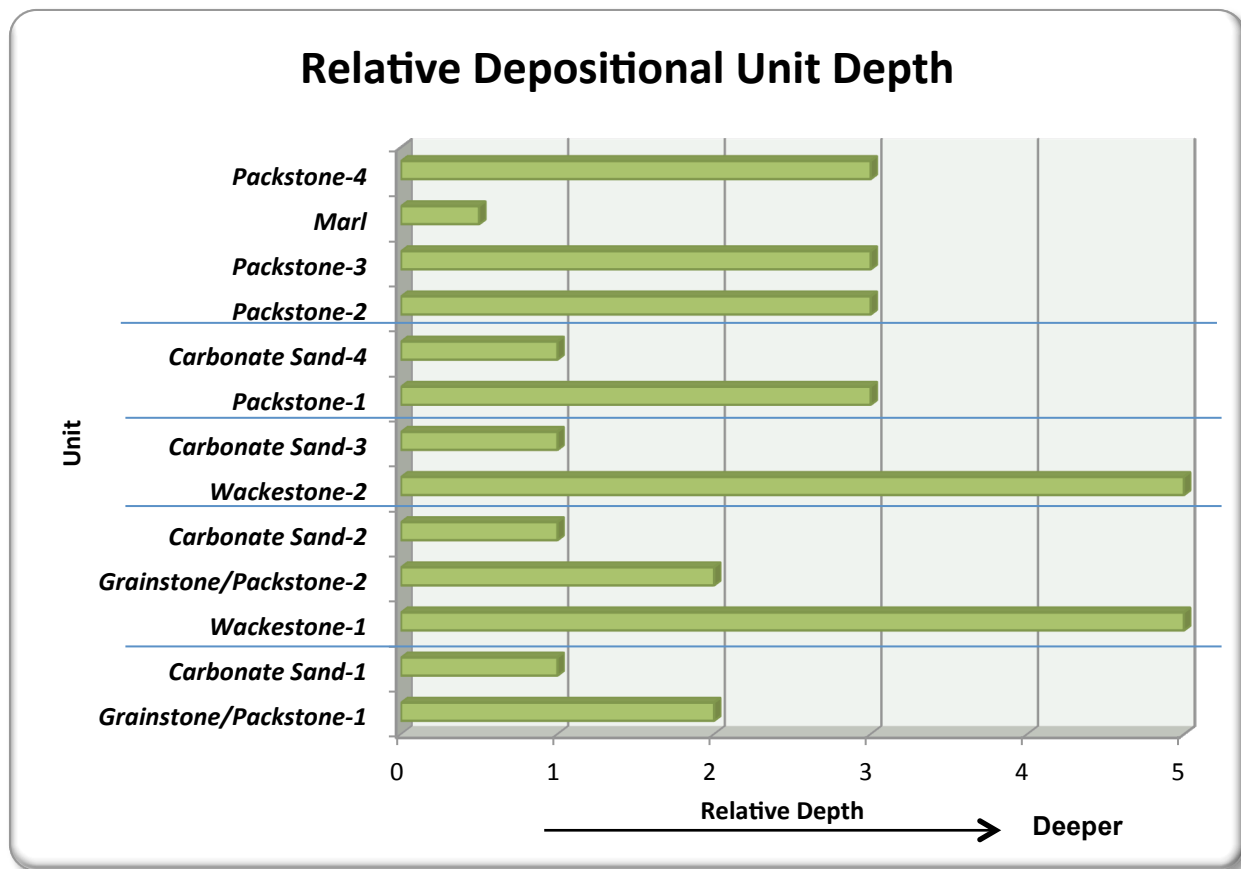


Chart 2 – Relative Depositional Unit Depth

The sedimentary layers can be grouped into five distinct depositional sequences. Each sequence begins with a deeper environment that grades into a shallower shoal environment. The sequences are depicted on Fig. 40. Each sequence is separated by a red line. Sequence 1 is possibly incomplete as no samples were acquired below the 98 foot level and borehole logs that penetrate to deeper levels are inconclusive. Sequence 5 is also possibly incomplete due to the erosion of the uppermost rock surface; whether this sequence shallows upward is unknown. Sequences 2, 3 and 4 represent complete shallowing upward sequences beginning with either wackestones or packstones and ending with carbonate sand shoals.

The five identified sequences are comparable to sequences identified by previous workers including Baum (1986), Zullo and Harris (1987) and LaGesse and Read (2006). These workers identified an Eocene super sequence consisting of five sub-sequences between the Cape Fear and Norfolk arches. LaGesse and Read (2006) identified the five sequences as E0 to E4 with E3 being comprised of two minor sequences. These five sequences mostly shallow upwards as do the five sequences identified at the Onslow quarry. LaGesse and Read (2006) identified hardgrounds as the basal boundary for most of their sequences. No hardgrounds were identified at Onslow Quarry. Above the hardgrounds a sequence typically begins with a wackestone-packstone or marl and terminates with a grainstone-packstone. These shallowing-upward lithologies are also seen at Onslow Quarry. The sequences at Onslow Quarry do differ in that they mostly terminate with an unconsolidated carbonate sand shoal deposit.

LaGesse and Read (2006), Zullo and Harris (1987), Harris, et al. (1993), Harris and Laws (1994), and Ward, et al. (1978) dated the Eocene sequences using nannoplankton zones. Sequences E0 and E1 were dated to zone NP 15, sequence E2 as NP 16, sequence E3a as NP 16 and NP 17, sequence E3b as NP 18 and sequence E4 as NP 19 and NP 20. The NP 15 zone is lower-middle Eocene which places the base of the E0 sequence in the Lutetian stage. The upper boundary is placed in either the late Eocene or middle Eocene, depending on the researcher.

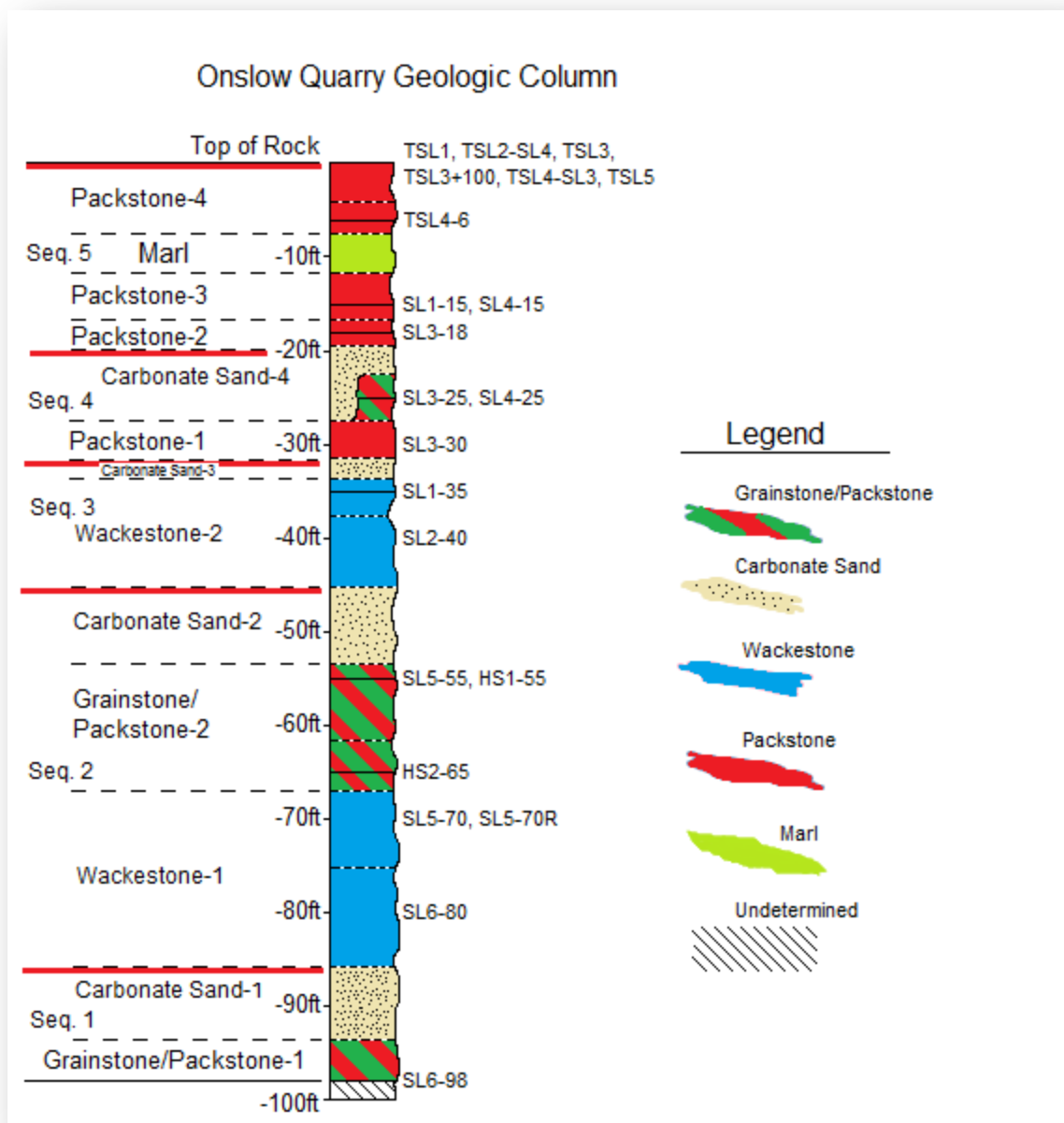


Figure 41 – Quarry Geologic Column with Depositional Sequences

Strontium Isotope Analysis

Shell fragments from three of the field samples, SL5-70R, SL6-98 and TSL5 were, sent to the Geochronology and Isotope Geochemistry Laboratory at the University of North Carolina at Chapel Hill for analysis of $^{87}\text{Sr}/^{86}\text{Sr}$. Two sets of analyses were run, a standard strontium seawater ratio analysis and a leachate analysis series. The standard analysis, indicating the age for each sample, is shown on Table 10.

The anomalous age for sample SL6-98 caused concern regarding possible later addition of strontium with $^{87}\text{Sr}/^{86}\text{Sr}$ different from seawater. The later addition of strontium not from Eocene seawater affected the strontium in the crystal matrices. Leaching experiments were run on each of the samples in order to examine this possibility. The results of these experiments are shown on Table 11. The leaching experiments progressively dissolve more of the sample. In well preserved samples with little diagenetic alteration there was very little change in the strontium isotope ratios but in samples with significant alteration, the ratios differed between leaching runs.

The results of the leaching experiments do indicate that the samples contain strontium from two or more sources. Had the samples been uncontaminated, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios would have been consistent for each progressive leaching run. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the leaching experiments are inconclusive as to the age of the samples. The ratios fall on regions of the strontium seawater curve (Chart 3) that differ from the known age of the sample.

Additional fossil samples were collected from location TSL1 in order to more accurately date the uppermost rock layer. Samples of bivalves, bryozoans, shark teeth and sand dollars were sent to the geochronology lab for analysis. One bivalve from this

second set of samples had a seawater ratio value that could place it in the upper age range for the Castle Hayne Formation. Experimental data for the second sample testing are included on Table 12. The bryozoans and echinoderms from the second group of samples were found not to fit the seawater curve and the shark teeth were not tested.

The strontium isotope testing was inconclusive due to the addition of strontium during multiple diagenetic events. Chart 4 shows the results of the analysis for the pecten shell. The average $^{87}\text{Sr}/^{86}\text{Sr}$ seawater ratio for the shell is 0.707724. This value places the shell in three possible positions on the strontium seawater curve as indicated on Chart 3. At two of the locations the value intersects the mean line of the curve. This allows for a preferred age to be assigned to the sample. The two preferred sample ages are 48.88 Ma and 52.56 Ma. These age dates would place the pecten shell in the Ypresian stage of the Eocene Epoch and would place the topmost layer of the rock strata at the quarry in the lower age range known for the Castle Hayne Limestone.

The date of 48.88 Ma places the pecten sample in either the lower part of the Comfort Member or the upper part of the New Hanover Member (Fig. 42). A date of 52.56 Ma would place the sample at a level below that previously observed for the Castle Hayne Formation. The date of 48.88 Ma is therefore the preferred age for the pecten sample. The age range on the strontium seawater curve for this sample is between 48.25 and 49.83 Ma.

A third position on the seawater curve between 38.54 Ma and 39.78 Ma also allows for a possible fit. This ratio does not intersect the mean line on the strontium seawater ratio curve (Chart 3), so the confidence level for this value is much lower and this age is less likely than the other two values.

Sample	Mean $^{87}\text{Sr}/^{86}\text{Sr}$	Age(ma)	Upper Age(ma)	Lower Age(ma)
TSL5	0.707817	34.26	33.88	34.94
SL5-70R	0.707813	34.37	33.95	35.15
SL6-98	0.707888	32.95	32.62	33.28

Table 10 – Strontium Isotope Analysis Ages

Sample	Test Run	Mean $^{87}\text{Sr}/^{86}\text{Sr}$	Corrected $^{87}\text{Sr}/^{86}\text{Sr}$
TSL5			
	1 Full	0.707817	0.707798
	2 Leach1	0.707853	0.707834
	3 Leach2	0.707779	0.707760
	4 Leach3	0.707791	0.707772
	5 Dissolution	0.707778	0.707759
SL5-70R			
	1 Full	0.707813	0.707794
	2 Leach1	0.707843	0.707824
	3 Leach2	0.707792	0.707773
	4 Leach3	0.707785	0.707766
	5 Dissolution	0.707802	0.707783
SL6-98			
	1 Full	0.707888	0.707869
	2 Leach1	0.707926	0.707907
	3 Leach2	0.707830	0.707811
	4 Leach3	0.707800	0.707781
	5 Dissolution	0.707798	0.707779

Table 11 – Leachate Experimental Results

Sample	Experiment Run	$^{87/86}\text{Sr}$ Ratio	Corrected $^{87/86}\text{Sr}$ Ratio
Pecten- 2	Full	0.707743	0.707724
	Leachate 1	0.707743	0.707724
	Leachate 2	0.707746	0.707727
	Leachate 3	0.707746	0.707727
	Leachate 4	0.707737	0.707718
Average:		0.707724	

Table 12 – Leachate Experimental Results for Second Sample

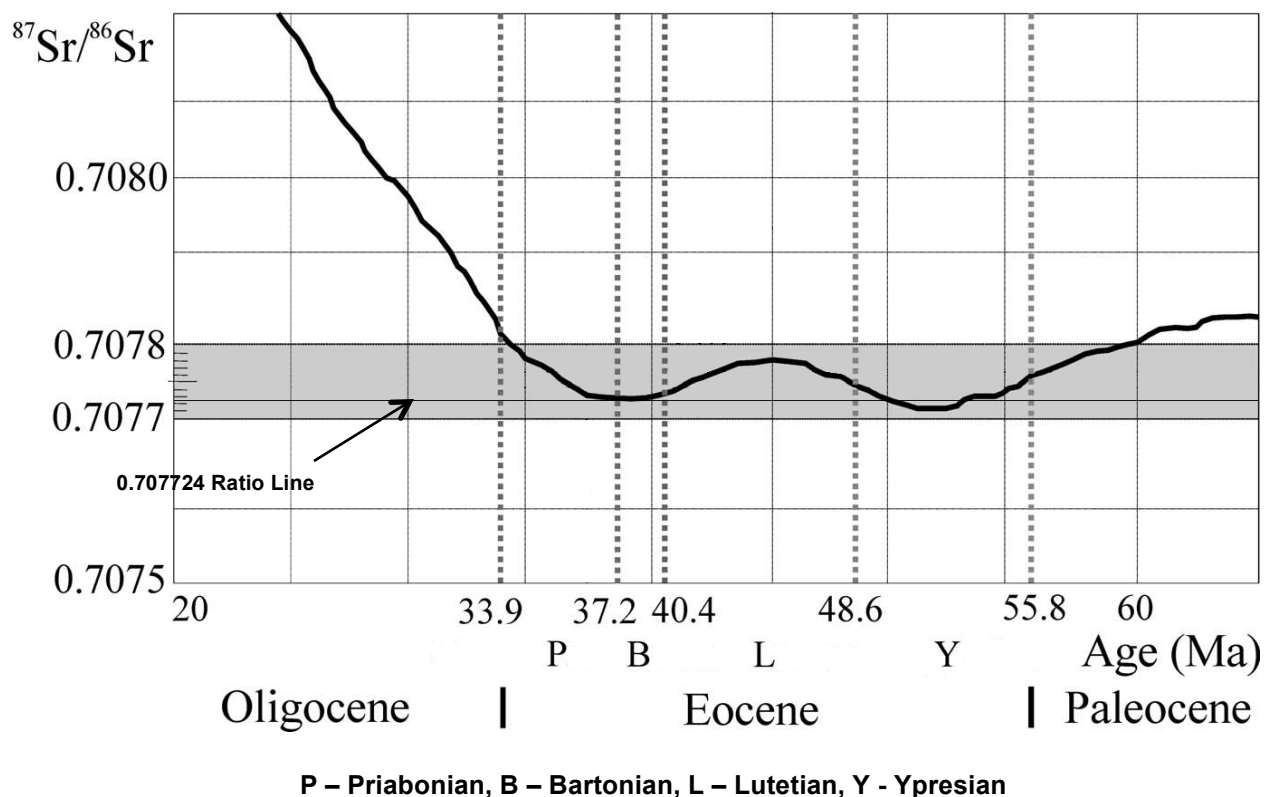


Chart 3 - Paleogene section of the seawater Sr evolution curve (LOWESS-fit; McArthur, et al., 2001) showing the low rate of change in marine $^{87}\text{Sr}/^{86}\text{Sr}$ values during Eocene time; Eocene time divisions from Gradstein and Ogg (2004). (Modified from Ravikant, and Bajpai, 2010)

The 2009 geologic time scale published by the Geologic Society of America (Walker and Geissman, 2009) sets the boundary between the Lutetian and Ypresian ages of the Eocene Epoch at 48.6 Ma. Harris and Fullagar (1989) used Rb-Sr and K-Ar isotope ratios to date bentonite and glauconite in the Castle Hayne Limestone, from the Fussell Quarry in Duplin County, North Carolina at 43.1 ± 1.2 Ma to 46.7 ± 1.8 Ma. Harris and Zullo (1982) used Rb-Sr and Sr-Sr ratios in glauconite to date the Comfort Member of the Castle Hayne in New Hanover County, North Carolina to 34.8 ± 1 Ma. This same formation was dated by Hazel, et al (1984) at 42.7 to 44.4 Ma by using a biostratigraphic-magnetostratigraphic-chronostratigraphic model. The preferred strontium ratio date obtained for the pecten sample at the Onslow Quarry places it

slightly below the date range determined by Harris and Fullagar (1989) and in the uppermost Ypresian age.

The date range of 48.25 to 49.83 Ma extracted from the pecten sample contradicts the age estimates made using nannoplankton zones by LaGesse and Read (2006), Zullo and Harris (1987), Harris, et al. (1993), Harris and Laws (1994), and Ward, et al. (1978). These researchers dated the lowermost Eocene sequence as lower-middle Eocene while the pecten sample is in the same approximate range but at the top of the sequences observed at the quarry which lends credence to the possibility that the third possible date range extracted from the pecten sample could in fact be an accurate date. A range of 38.54 to 39.78 Ma coincides more closely with the NP 19 and NP 20 nannoplankton zone date ranges estimated for the E4 sequence.

The date range of 48.25 and 49.83 Ma for the pecten sample places the upper level of the formation at the quarry in the lower date range for the Castle Hayne Formation which implies that either all Eocene deposition in the vicinity of the quarry ended then or any additional deposits have been eroded. An examination of the cross section of Eocene strata in Onslow County (Fig. 27) reveals that the thickness of the Castle Hayne at the quarry and in USGS borehole NC-ON-T-27, approximately 100 feet, is much less than the thickness of the formation found in boreholes NC-ON-OT-23 and NC-ON-OT-24, which are approximately 10 miles south of the quarry. The possibility exists that the formation has undergone more erosion in the vicinity of the quarry than it has farther to the south.

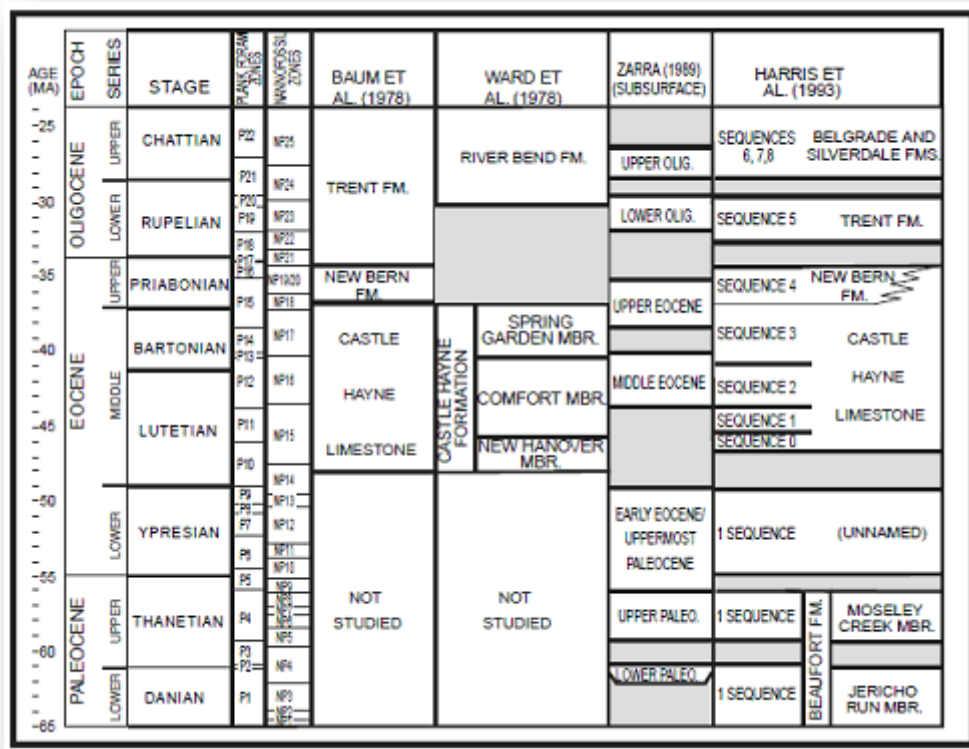


Figure 42 - Paleogene Stratigraphic Nomenclature beneath the North Carolina Coastal Plain – from Berggren et al., 1995

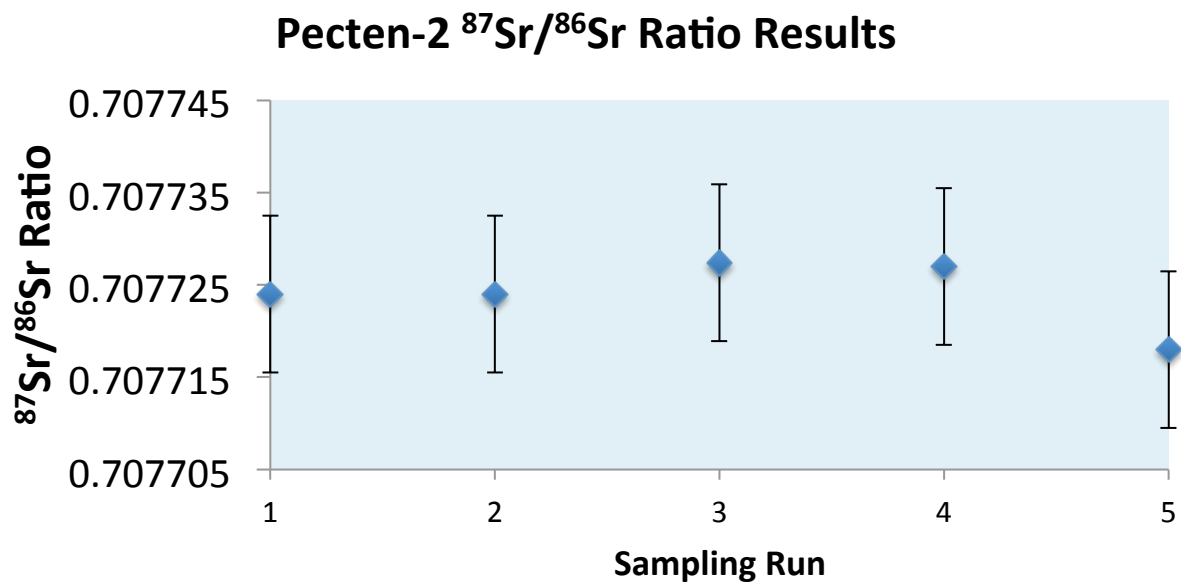


Chart 4 – Pecten Shell Sampling Results – From Inglis, J.D., 2012

Conclusions

The geology of the quarry south of Richlands, North Carolina was studied using field sample analysis, borehole data analysis, photographic imagery analysis and strontium isotope analysis. These data were combined to form an interpretation of the geology present at the quarry.

The rock extracted from the quarry is a fossil rich limestone. The lowermost depth of the quarried rock is approximately 120 to 140 feet below land surface where it changes to sands and marls possibly of the Late Cretaceous Peedee Formation. The limestone comprises an upper unit and a lower unit composed of numerous sub-units. The limestone units are separated by a poorly indurated wackestone (marl) unit that appears to have been deposited in a near shore lagoonal environment. The marl unit also has a sand lens that is interpreted to be a beach sand. The limestone layers are very fossiliferous with bryozoans, echinoderms, bivalves, gastropods, foraminifera and corals. Sand dollars and shark teeth also occur in the uppermost layers.

The limestone, carbonate sand and poorly indurated wackestone (marl) units were assigned to microfacies zones using the homoclinal carbonate ramp model of Flügel (2004). Changes in water depth either due to global sea level fluctuations, regional tectonic activity, or changes caused by sediment accumulation are the likely causes for the facies zone changes.

Five shallowing upward depositional sequences were identified, each beginning with a deeper unit representative of a flooding event. Four of the sequences end with a carbonate sand unit indicative of shallowing. The uppermost sequence is incomplete, due to post-depositional erosion.

Age dating of fossils using strontium isotope analysis has indicated that the uppermost rock layer is between 48.25 and 49.83 Ma. This places the uppermost rock strata in either the lower part of the Comfort Member or the upper part of the New Hanover Member and indicates that extensive erosion of the Castle Hayne Formation has occurred in the quarry area.

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Appendix A: Thin Section Point Counting Data

SL1-15		
	Points	%
Matrix	213	46.3
Voids	29	6.3
Echinoderms	35	7.6
Bryozoans	99	21.5
Bivalves	29	6.3
Gastropods	18	3.9
Foraminifera	1	0.2
Quartz	7	1.5
Glauconite	1	0.2
Other Intraclasts	16	3.5
U/I Bioclasts	12	2.6
Total Points:	460	100.0

SL1-35		
	Points	%
Matrix	178	41.5
Voids	77	17.9
Echinoderms	48	11.2
Bryozoans	48	11.2
Bivalves	17	4.0
Gastropods	11	2.6
Foraminifera	3	0.7
Quartz	12	2.8
Glauconite	6	1.4
Other Intraclasts	18	4.2
U/I Bioclasts	11	2.6
Total Points:	429	100.0

SL2-40		
	Points	%
Matrix	216	52.2
Voids	68	16.4
Echinoderms	40	9.7
Bryozoans	49	11.8
Bivalves	9	2.2
Gastropods	2	0.5
Foraminifera	2	0.5
Quartz	5	1.2
Glauconite	3	0.7
Other Intraclasts	8	1.9
U/I Bioclasts	12	2.9
Total Points:	414	100.0

SL3-18		
	Points	%
Matrix	175	36.5
Voids	96	20.0
Echinoderms	67	14.0
Bryozoans	49	10.2
Bivalves	5	1.0
Gastropods	6	1.3
Foraminifera	3	0.6
Quartz	13	2.7
Glauconite	7	1.5
Other Intraclasts	13	2.7
U/I Bioclasts	45	9.4
Total Points:	479	100.0

SL3-30		
	Points	%
Matrix	221	51.8
Voids	30	7.0
Echinoderms	39	9.1
Bryozoans	62	14.5
Bivalves	16	3.7
Gastropods	3	0.7
Foraminifera	2	0.5
Quartz	3	0.7
Glauconite	7	1.6
Other Intraclasts	12	2.8
U/I Bioclasts	32	7.5
Total Points:	427	100.0

SL4-15		
	Points	%
Matrix	202	42.2
Voids	44	9.2
Echinoderms	76	15.9
Bryozoans	46	9.6
Bivalves	14	2.9
Gastropods	10	2.1
Foraminifera	3	0.6
Quartz	22	4.6
Glauconite	10	2.1
Other Intraclasts	12	2.5
U/I Bioclasts	40	8.4
Total Points:	479	100.0

SL4-25		
	Points	%
Matrix	188	41.0
Voids	82	17.9
Echinoderms	37	8.1
Bryozoans	81	17.7
Bivalves	14	3.1
Gastropods	3	0.7
Foraminifera	5	1.1
Quartz	10	2.2
Glauconite	8	1.7
Other Intraclasts	2	0.4
U/I Bioclasts	28	6.1
Total Points:	458	100.0

SL5-55		
	Points	%
Matrix	114	26.1
Voids	122	27.9
Echinoderms	45	10.3
Bryozoans	43	9.8
Bivalves	6	1.4
Gastropods	13	3.0
Foraminifera	3	0.7
Quartz	38	8.7
Glauconite	9	2.1
Other Intraclasts	18	4.1
U/I Bioclasts	26	5.9
Total Points:	437	100.0

SL5-70		
	Points	%
Matrix	273	56.8
Voids	29	6.0
Echinoderms	21	4.4
Bryozoans	45	9.4
Bivalves	15	3.1
Gastropods	8	1.7
Foraminifera	14	2.9
Quartz	22	4.6
Glauconite	19	4.0
Other Intraclasts	25	5.2
U/I Bioclasts	10	2.1
Total Points:	481	100.0

SL5-70R		
	Points	%
Matrix	168	35.3
Voids	133	27.9
Echinoderms	39	8.2
Bryozoans	43	9.0
Bivalves	23	4.8
Gastropods	17	3.6
Foraminifera	2	0.4
Quartz	21	4.4
Glauconite	7	1.5
Other Intraclasts	4	0.8
U/I Bioclasts	19	4.0
Total Points:	476	100.0

SL6-80		
	Points	%
Matrix	158	38.1
Voids	36	8.7
Echinoderms	33	8.0
Bryozoans	62	14.9
Bivalves	25	6.0
Gastropods	4	1.0
Foraminifera	1	0.2
Quartz	59	14.2
Glauconite	7	1.7
Other Intraclasts	13	3.1
U/I Bioclasts	17	4.1
Total Points:	415	100.0

SL6-98		
	Points	%
Matrix	138	26.4
Voids	185	35.4
Echinoderms	14	2.7
Bryozoans	31	5.9
Bivalves	0	0.0
Gastropods	2	0.4
Foraminifera	3	0.6
Quartz	115	22.0
Glauconite	13	2.5
Other Intraclasts	14	2.7
U/I Bioclasts	8	1.5
Total Points:	523	100.0

TSL1		
	Points	%
Matrix	115	28.0
Voids	142	34.6
Echinoderms	55	13.4
Bryozoans	52	12.7
Bivalves	0	0.0
Gastropods	5	1.2
Foraminifera	1	0.2
Quartz	3	0.7
Glauconite	14	3.4
Other Intraclasts	6	1.5
U/I Bioclasts	17	4.1
Total Points:	410	100.0

TSL2-SL4		
	Points	%
Matrix	281	49.9
Voids	48	8.5
Echinoderms	63	11.2
Bryozoans	63	11.2
Bivalves	20	3.6
Gastropods	12	2.1
Foraminifera	14	2.5
Quartz	22	3.9
Glauconite	21	3.7
Other Intraclasts	9	1.6
U/I Bioclasts	10	1.8
Total Points:	563	100.0

TSL3		
	Points	%
Matrix	357	52.9
Voids	71	10.5
Echinoderms	33	4.9
Bryozoans	24	3.6
Bivalves	4	0.6
Gastropods	3	0.4
Foraminifera	52	7.7
Quartz	22	3.3
Glauconite	35	5.2
Other Intraclasts	10	1.5
U/I Bioclasts	64	9.5
Total Points:	675	100.0

TSL3+100		
	Points	%
Matrix	305	53.9
Voids	53	9.4
Echinoderms	14	2.5
Bryozoans	32	5.7
Bivalves	2	0.4
Gastropods	11	1.9
Foraminifera	41	7.2
Quartz	34	6.0
Glauconite	30	5.3
Other Intraclasts	1	0.2
U/I Bioclasts	43	7.6
Total Points:	566	100.0

TSL4-SL3		
	Points	%
Matrix	263	50.9
Voids	65	12.6
Echinoderms	39	7.5
Bryozoans	60	11.6
Bivalves	6	1.2
Gastropods	19	3.7
Foraminifera	4	0.8
Quartz	14	2.7
Glauconite	11	2.1
Other Intraclasts	2	0.4
U/I Bioclasts	34	6.6
Total Points:	517	100.0

TSL4-6		
	Points	%
Matrix	339	69.6
Voids	55	11.3
Echinoderms	5	1.0
Bryozoans	37	7.6
Bivalves	4	0.8
Gastropods	6	1.2
Foraminifera	22	4.5
Quartz	1	0.2
Glauconite	2	0.4
Other Intraclasts	3	0.6
U/I Bioclasts	13	2.7
Total Points:	487	100.0

TSL5		
	Points	%
Matrix	252	45.2
Voids	81	14.5
Echinoderms	15	2.7
Bryozoans	128	22.9
Bivalves	30	5.4
Gastropods	19	3.4
Foraminifera	6	1.1
Quartz	8	1.4
Glauconite	2	0.4
Other Intraclasts	1	0.2
U/I Bioclasts	16	2.9
Total Points:	558	100.0

HS1-55		
	Points	%
Matrix	190	40.3
Voids	93	19.7
Echinoderms	10	2.1
Bryozoans	98	20.8
Bivalves	11	2.3
Gastropods	23	4.9
Foraminifera	1	0.2
Quartz	20	4.2
Glauconite	6	1.3
Other Intraclasts	5	1.1
U/I Bioclasts	15	3.2
Total Points:	472	100.0

Appendix B: Thin Section Descriptions

Slide: SL1-15

General Description

Micritic matrix; generally dense; bivalve molds; bryozoans; small gastropods; foraminifera; solution seams; rounded quartz grains; glauconite pellets; echinoderms; bivalve molds are predominately unfilled; opaque matter, pyrite; biomicrudite

Fossil Descriptions

Bivalves:

- Dogtooth spar cement common along edges
- Varying degrees of filling of mollusk molds by dogtooth and granular spar cements
- Some bivalve molds have no dogtooth spar cement, only granular spar cement
- Some bivalve molds are completely filled with dogtooth/granular spar cements
- Some molds have been enlarged creating vugs

Gastropods:

- Void space filled with micrite
- Shell dissolved, partially filled with dogtooth spar or completely filled with granular spar

Bryozoans:

- Void spaces are predominantly filled with granular/dogtooth spar

Observational Notes

- Some clear isotropic clasts, possibly halite or fluorite
- A possible geopetal in a bivalve mold
- One indication of dogtooth spar overgrown granular spar
- Quartz and glauconite appear to be clastic

Diagenetic Activity

- Severe fracturing of shells and skeletons during deposition and compaction
- Authigenic pyrite formed in and adjacent to shells, skeletons and glauconite pellets
- Lime mud lithification to micrite
- Bivalve and gastropod shells dissolved forming molds
- High Mg echinoderm plates replaced by low Mg-calcite with some syntaxial overgrowths
- Bryozoan skeletons replaced by microspar
- Some gastropod shells replaced by microspar
- Bivalve molds lined with dogtooth spar with some grading to equant and or granular mosaic fabrics
- Bivalve molds enlarged beyond mold boundaries
- Micrite filling in bryozoan fans with aggrading neomorphism to microspar

Slide: SL 1-35

General Description

Micritic matrix; bivalves; echinoderms; gastropods; bryozoans; foraminifera; rounded quartz grains; opaque matter; intraclasts; glauconite; biomicrudite

Fossil Descriptions

Bivalves:

- Bivalve shells have dissolved resulting in molds
- Molds lined with dogtooth/granular spar
- Dissolution beyond shell boundaries of many bivalves, which has created a vuggy fabric

Bryozoans:

- Voids filled with micrite
- Skeleton replacement by granular spar

Observational Notes

- Possible peloid
- Quartz and glauconite appear to be clastic

Diagenetic Activity

- Severe fracturing of shells and skeletons during deposition and compaction
- Authigenic pyrite in and adjacent to shells, skeletons and glauconite pellets
- Lime mud lithification to micrite
- Bivalve shell replacement by microspar
- Echinoderm plate calcite replacement by low-Mg calcite microspar
- Bryozoan skeletal replacement by microspar
- Gastropod shell replacement by microspar
- Bivalve microspar dissolution, mold edges coated with dogtooth and granular spar cements
- Gastropod microspar dissolution, molds lined with dogtooth and granular spar cements
- Bivalve mold enlargement beyond original mold boundaries has created a vuggy fabric
- Some bryozoan microspar has dissolved

Slide: SL2-40

General Description

Micritic matrix; bivalve molds; bryozoans; rounded quartz grains; foraminifera; solution seams; glauconite grains; opaques – pyrite; biomicrudite

Fossil Descriptions

Bivalves:

- Shells dissolution created molds
- Voids partially to completely filled by dogtooth and granular spar cements
- Enlargement of voids beyond shell boundaries creating vugs

Gastropods:

- Micrite void filling
- Shell replacement by granular spar
- Dissolution of micrite filling
 - Replaced by granular and dogtooth spar cements

Bryozoans:

- Void filling by granular spar and opaques
- Diagenetic sequence:
 - Voids filled with micrite
 - Granular spar replacement of skeleton
 - Dissolution of spar
 - Dissolution of micrite
 - End result was a void

Observational Notes

- Granular spar has coated some opaques
- Bioclasts were initially micritized
- Quartz and glauconite grains are clastic
- Some pores show neomorphism of micrite to microspar and spar
 1. Microspar may have been replaced by opaques
 2. Opaques, possibly pyrite, then began to dissolve

Diagenetic Activity

- Severe fracturing of shells and skeletons during deposition
- Authigenic pyrite forming in and adjacent to shells and skeletons
- Lime mud lithification to micrite
- Bivalve shell dissolution
- Echinoderm plate replacement by calcite
- Bryozoan skeletal replacement by microspar
- Gastropod shell replacement by microspar
- Solution seams
- Dissolution of gastropod replacement microspar
- Dogtooth spar lining of expanding bivalve molds
- Vuggy fabric developing from bivalve and gastropod shell dissolution
- Bryozoan void space filling micrite neomorphing to microspar
- Authigenic pyrite forming in micrite matrix
- Some dogtooth and granular spar forming in bivalve mold voids

Slide: SL3-18

General Description

Partially micritic matrix; micrite filling initially with replacement by spar; bryozoans; gastropods; bivalves; skeletons initially micritized and filled with micrite; neomorphism of micrite matrix to dogtooth and granular spar; further dissolution has created voids; quartz; opaques, glauconite; intraclasts; biosparrudite

Fossil Descriptions

Gastropods:

- Micrite void filling
- Shell replacement by microspar and spar
- Some dissolution of skeletal spar

Bivalves:

- Shell dissolution has created molds
- Molds partially to completely filled with granular spar

Bryozoans:

- Micrite void fillings have undergone neomorphism to microspar
- Diagenetic opaques forming in voids – possibly pyrite

Echinoderms:

- Replacement by calcite

Observational Notes

- Extensive diagenetic opaques in matrix
- Quartz and glauconite are depositional
- Micrite envelopes outline many bioclasts
 - Remain as skeletal interiors become spar filled or even dissolved leaving voids

Diagenetic Activity

- Fracturing and breakage of shells and skeletons during deposition
- Micritic envelopes forming around shells and skeletons
- Authigenic pyrite forming in and adjacent to shells, skeletons and glauconite grains and pellets
- Lime mud lithification to micrite
- Void spaces in shells and skeletons filled with micrite
- Bivalves and gastropods dissolved
- Microspar replacement of bryozoan skeletons
- Calcite replacement of echinoderm plates with some syntaxial overgrowths
- Authigenic pyrite formed in micrite matrix
- Micrite has undergone neomorphism to microspar in matrix and bryozoans
- Some dogtooth spar along mold linings
- Mold expanded beyond void boundaries, vuggy fabric developed

Slide: SL3-30

General Description

Micrite matrix; more bivalves than SL3-18; bryozoans; foraminifera; gastropods; intraclasts; rounded quartz; opaques – pyrite; isotropic clasts; echinoderms; glauconite pellets; biomicrudite.

Fossil Descriptions

Bivalves:

- Micrite envelopes
- Dissolution of shells
- Dogtooth spar lining
 - Varying in size by mold
- Some dogtooth spar grades to granular spar which filled the mold
- Some dogtooth spar is quite large

Bryozoans:

- Some show very minimal or no neomorphism to microspar beyond initial micritization
- Others show neomorphism to granular spar and some dissolution
- Accumulations of opaques in voids

Gastropods:

- Some replacement of small gastropods by opaques

Observational Notes

- Some neomorphism of micrite to spar in matrix with further dissolution
- Large intraclasts appear to consist mainly of quartz grains
- Quartz and glauconite are clastic

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Micrite envelopes around bivalves
- Authigenic pyrite forming in and adjacent to shells and skeletons
- Lime mud lithification to micrite
- Bivalve shell dissolution
- Calcite replacement of echinoderm plates
- Microspar replacement of bryozoan skeletons
- Filling of bivalve molds first with dogtooth spar and then granular spar
- Micrite in bryozoans has undergone neomorphism to microspar and then dissolved
- Micrite matrix has undergone neomorphism to microspar and spar

Slide: SL4-15

General Description

Micrite and microspar matrix; bryozoans; ooid; echinoderms; gastropods; bivalves; isotropic clasts; glauconite; quartz; less voids than other samples; biomicrudite

Fossil Descriptions

Gastropods:

- Voids filled with micrite
- Micrite envelopes
- Dogtooth spar filling of void linings

Echinoderms:

- Plate replacement by spar calcite

Observational Notes

- Dogtooth and granular spar linings in voids
- Micrite and microspar matrix have undergone neomorphism to granular and dogtooth spar with some further dissolution
- Significant opaque precipitation in and around bryozoans as well as the ooid
- Micrite envelopes around bivalves
- Granular spar has filled bivalves
- Quartz and glauconite are clastic

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Micritic envelopes formed around shells and skeletons
- Authigenic pyrite formed in and adjacent to shells, skeletons and glauconite grains
- Lime mud lithification to micrite
- Microspar replacement of bryozoan skeletons
- Calcite replacement of echinoderm plates
- Some dissolution of bivalve shells
- Bivalve molds filled with dogtooth and then granular spar
- Micrite matrix underwent neomorphism to dogtooth and granular spar
- Some dissolution of spar matrix

Slide: SL4-25

General Description

Original micrite matrix; bryozoans; echinoderms; solution seams; bivalves; rounded quartz grains; glauconite pellets; opaques – pyrite; opaque intraclasts; feldspar intraclast; gastropods; biomicrudite

Fossil Descriptions

Bivalves:

- Shell dissolution
- Filling with dogtooth and granular spar
- Partial to complete filling of voids

Bryozoans:

- Micritization
 - Partial pore dissolution
 - Partial filling with microspar
- Some pore filling with micrite
 - Skeleton replacement with granular spar
 - Also some pore replacement of micrite by granular spar

Echinoderms:

- Spar replacement of plates

Matrix:

- Replacement by dogtooth and granular spar
- Further dissolution has created vuggy porosity
 - Some vugs visibly connected

Observational Notes

- Euhedral anhydrite? crystals radiating from center point
- Quartz and glauconite is clastic

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Micrite envelopes formed around shells and skeletons
- Authigenic pyrite formed in and adjacent to shells, skeletons and glauconite grains
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates
- Microspar replacement of bryozoan skeletons
- Dissolution of bivalve and gastropod shells
- Micrite in bryozoans underwent neomorphism to microspar
- Dogtooth and granular spar filled bivalve molds
- Matrix micrite underwent neomorphism to microspar
- Dissolution of matrix microspar, vuggy fabric developed
- Anhydrite? crystals formed in vuggy fabric

Slide: SL5-55

General Description

Some evidence for an original micritic matrix; bryozoans; bivalves; echinoderms; intraclasts; rounded quartz grains; opaques – possibly pyrite; gastropods; clear isotropic clast; radiating euhedral quartz crystals; biosparrudite

Fossil Descriptions

Gastropods:

- Micrite filling of voids
- Micritic envelope
- Skeletal dissolution
- Dogtooth spar linings
- Some neomorphism of micrite to microspar

Bivalves:

- Shell dissolution
- Granular and dogtooth spar lining of voids

Echinoderms:

- Plate replacement by calcite

Bryozoans:

- Microspar filling of voids
- Skeletal replacement by microspar
- Some void micrite neomorphism to microspar

Matrix

- Has undergone neomorphism to microspar

Observational Notes

- Some voids show isopachous dogtooth spar lining
- Vuggy porosity developing from bivalves and matrix
- Lesser numbers of bryozoans
- Isopachous dogtooth spar more common around echinoderms
- Glauconite and quartz are clastic

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Micrite rims formed around shells and skeletons
- Authigenic pyrite formed in and adjacent to shells, skeletons and glauconite grains
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates with some syntaxial overgrowths
- Microspar replacement of bryozoan skeletons
- Dissolution of bivalve and gastropod shells
- Neomorphism of matrix micrite to microspar and spar
- Dogtooth and granular spar filling of bivalve and gastropod molds
- Microspar neomorphism of bryozoan micrite
- Dissolution of bryozoan skeletal microspar
- Dissolution of spar in molds
- Dissolution of matrix microspar
- Vuggy fabric formed throughout matrix
- Anhydrite? crystals formed in vuggy fabric

Slide: HS1-55

General Description

Gastropods; intraclasts; bryozoans; echinoderms; quartz grains; glauconite; bivalves; opaques; some micrite envelopes; originally a micrite matrix

Fossil Descriptions

Gastropods:

- Micrite envelope
- Some voids micrite filled but mostly dissolved or undergone neomorphism to microspar

Bryozoans:

- Micritization
- Micrite void filling
- Neomorphism of micrite to microspar has begun

Bivalves:

- Shell dissolution
- Voids lined with dogtooth and granular spar
- Some micrite envelopes

Echinoderms:

- Replacement by calcite

Observational Notes

Matrix:

- Neomorphism to microspar and spar calcite
- Dissolution with dogtooth linings of voids
- Vuggy voids developed in matrix with dogtooth lining
- Minimal glauconitization

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Some micritic rims formed around shells
- Authigenic pyrite formed in and adjacent to bryozoans
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates with some syntaxial overgrowths
- Microspar and micrite replacement of bryozoan skeletons
- Dissolution of bivalve and gastropod shells
- Filling of gastropod molds with microspar
- Filling of bivalve molds with dogtooth and granular spar
- Neomorphism of micrite in bryozoan voids to microspar
- Matrix has undergone extensive neomorphism to microspar and spar calcite
- Some glauconitization in matrix and bryozoans
- Some dissolution of matrix and bryozoans

Slide: SL5-70

General Description

Micrite matrix; intraclasts; bryozoans; echinoderms; rounded quartz grains; bivalves; foraminifera; clear isotropic clasts; glauconite; gastropods; opaques – possibly pyrite; solution seams; possibly small dolomite rhombs; biomicrudite

Fossil Descriptions

Bryozoans:

- Microspar replacement of skeleton
- Microspar filling in voids
- Some micrite filling in voids
- Some partial dissolution of skeletons

Echinoderms:

- Replacement by spar
- No visible dissolution

Bivalves:

- Shell dissolution
- Void lining with dogtooth and granular spar
- Some molds filled with micrite
- Some molds filled with dogtooth and granular spar

Gastropods:

- Void filling with micrite
- Shells replaced by granular and dogtooth spar
- Some shell dissolution
- Some shells appear to be replaced by microspar

Foraminifera:

- Micritized
- Some possible filling with glauconite

Observational Notes

- Fewer void spaces than many samples
- Some voids appear vuggy
- Small pyrite grains common in bryozoans
- Larger pyrite grains appear as authigenic growths in voids
- Micrite filling in one bivalve has partially dissolved
- Foraminifera are common in the matrix

- A few micrite envelopes surround bivalve molds with partial to complete dissolution and dogtooth/granular spar lining

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Some micrite envelopes formed around bivalve shells
- Authigenic pyrite formed in and adjacent to shells, skeletons and glauconite grains
- Lime mud lithification to micrite
- Dissolution of bivalve shells formed molds
- Calcite replacement of echinoderm plates with some syntaxial overgrowths
- Microspar replacement of bryozoan skeletons and gastropod shells
- Granular spar replacement of bivalve shells
- Degrading neomorphism of granular spar in bivalve shells to micrite
- Microspar neomorphism of some micritic matrix
- Some voids formed in microspar matrix with dogtooth calcite linings

Slide: *SL5-70R*

General Description

Evidence for a micritic matrix; bivalves; gastropods; intraclasts; glauconite; echinoderms; bryozoans; sub-angular and rounded quartz grains; micrite envelopes; solution seams; authigenic opaques; foraminifera; biosparrudite

Fossil Descriptions

Bivalves:

- Micrite envelopes
- Dissolved shells
- Dogtooth and granular spar void linings

Gastropods:

- Micrite filled voids
- Shells dissolved
 - Partially filled with dogtooth and granular spar
- Micrite envelopes

Echinoderms:

- Spar replacement of plates

Bryozoans:

- Micrite filling
- Microspar replacement of skeletons

Foraminifera:

- Replacement by microspar with loss of detail

Matrix:

- Undergone neomorphism to granular and dogtooth spar
- Dogtooth spar lining larger voids

Observational Notes

- Large vuggy voids common in matrix
- Very little dissolution of echinoderms and bryozoans
- Some bryozoans appear micritized

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Micrite envelopes formed around shells and skeletons
- Authigenic pyrite formed in and adjacent to shells, skeletons and glauconite grains
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates with some syntaxial overgrowths
- Microspar replacement of bryozoan skeletons
- Granular spar replacement of bivalve and gastropod shells
- Neomorphism of micrite matrix to microspar
- Dissolution of bivalve and gastropod microspar with dogtooth spar linings
- Dissolution of matrix microspar created vuggy fabric

Slide: SL6-80

General Description

Original micrite matrix; micrite rims; bryozoans; sub-angular/rounded quartz grains; echinoderms; intraclasts; glauconite; bivalves; gastropods; opaques; pyritization; solution seams; biosparrudite

Fossil Descriptions

Gastropods:

- Microspar skeletal replacement
- Voids partially filled with granular and dogtooth spar

Bryozoans:

- Micritization of skeletons
- Granular microspar void filling replacing micrite

Bivalves:

- Some micrite rims
- Granular spar linings
- Shells dissolved
- Some dogtooth spar
- Some filled with equant mosaic spar

Unidentified Bioclast:

- Micrite envelope
- Microspar filling
- Partial dissolution of microspar
 - Possibly a gastropod

Echinoderms:

- Spar replacement of plates
- Some syntaxial overgrowths

Observational Notes

- Vugs developed in matrix
- Some voids show dogtooth spar growths
- Appears to be some pyritization
- Bryozoans are the dominant bioclast form
- Most voids are smaller than those in other samples
- Few bivalves evident
- Quartz and glauconite are clastic

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Micrite envelopes around shells and skeletons
- Authigenic pyrite formed in and adjacent to shells, skeletons and glauconite grains
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates with some syntaxial overgrowths
- Microspar replacement of bryozoan skeletons
- Dissolution of some bivalve shells
- Spar replacement of bivalve shells
- Neomorphism of micritic matrix to granular spar – this is mostly complete through the slide
- Neomorphism of micrite in bryozoans to microspar

Slide: SL6-98

General Description

Matrix originally micrite; bryozoans; gastropods; intraclasts; rounded quartz grains; opaques; potentially bivalves but molds are dissolved beyond mold edges; possibly echinoderms; glauconite; biosparrudite

Fossil Descriptions

Bryozoans:

- Micritic and microspar skeletons
- Microspar void fillings
- Some pyritization
- Some skeletal dissolution

Gastropods:

- Micrite void fillings
- Dissolution of shells
- Dogtooth spar along void linings

Bivalves:

- Any bivalves are completely dissolved
- Large voids show some resemblance to bivalve molds but are expanding as large vugs

Echinoderms:

- Minimal evidence
- A few appear to exhibit calcite replacement of plates

Observational Notes

- Possibly some foraminifera
- Sample is very vuggy
- Void linings with dogtooth spar
- Clastic quartz is very common

Diagenetic Activity

- Breakage of shells and skeletons
- Authigenic pyrite formed in and adjacent to shells and skeletons
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates (minimal)
- Microspar replacement of bryozoan skeletons
- Dissolution of gastropod shells
- Neomorphism of matrix to microspar
- Dissolution of matrix creating a very vuggy fabric

Slide: TSL1

General Description

Micrite matrix; gastropods; intraclasts; echinoderms; bryozoans; coral; bivalves; glauconite pellets; micrite envelopes; biosparrudite

Fossil Descriptions

Gastropods:

- Micrite void filling
- Shell replacement by microspar

Echinoderms:

- Replacement of plates by spar calcite
- Possible limited silicification

Bryozoans:

- Skeletal micritic replacement
- Voids filled with micrite
- Some dissolution of skeletons

Observational Notes

- Large voids lined with granular and dogtooth spar
- Matrix highly dissolved
 - Some neomorphism to microspar

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Formation of micrite envelopes around shells and skeletons
- Authigenic pyrite formation in and adjacent to shells, skeletons and glauconite grains
- Lime mud lithification to micrite
- Calcite replacement of echinoderms
- Microspar replacement of bryozoans
- Neomorphism of micrite matrix to microspar
- Dissolution of matrix microspar has created a very vuggy fabric

Slide: TSL2-SL4

General Description

Micrite matrix; foraminifera in matrix; echinoderms; bryozoans; bivalves; glauconite pellets; rounded quartz grains; gastropods; intraclasts; opaques – pyrite; biomicrudite

Fossil Descriptions

Echinoderms:

- Replacement by spar calcite

Bryozoans:

- Micrite skeletal replacement
- Microspar in voids

Bivalves:

- Shells dissolved
- Voids partially to completely filled with granular, and in places dogtooth spar

Gastropods:

- Voids filled with micrite
- Shell replacement with granular spar
- Some dissolution of granular spar
- Some dogtooth spar

Foraminifera:

- Test replacement by microspar
- Micrite void fillings

Observational Notes

- Voids confined mostly to shells
- Micrite matrix shows little neomorphism to microspar
- Pyritization In some voids of microspar
- Solution seam with pyrite

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Some micrite envelopes
- Authigenic pyrite formed in and adjacent to shells and skeletons
- Lime mud lithification to micrite
- Microspar replacement of gastropods, bivalves and bryozoans
- Dissolution of microspar in gastropods, bivalves and bryozoans

Slide: TSL3

General Description

Micrite matrix; gastropods, foraminifera; echinoderms; quartz; coral; bryozoans; glauconite; biomicrudite

Fossil Descriptions

Gastropods:

- Micrite shell with microspar void filling
- One specimen shows complete dissolution of shell with dogtooth/granular lining

Coral

- Replacement by calcite

Observational Notes

- Fossils are generally well preserved
- Minimal skeletal dissolution
- Small voids have grown in matrix that has become lined with granular spar
- Some glauconitization
- One long skeleton (unidentified) shows voids with dogtooth/granular lining

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Authigenic pyrite formed on glauconite pellets
- Lime mud lithification to micrite
- Calcite replacement of echinoderms and corals
- Microspar replacement of bryozoan skeletons and gastropod shells and foraminifera
- Dissolution of micrite in matrix and shells
- Dissolution and reprecipitation of micrite in matrix

Slide: TSL3+100

General Description

Similar to TSL3; micrite matrix; coral; echinoderms; foraminifera; bryozoans; quartz; glauconite; opaques – pyrite; biosparrudite

Fossil Descriptions

Coral

- Replacement by calcite

Echinoderms

- Plate replacement by calcite

Bryozoans

- Skeleton replacement by microspar

Observational Notes

- Quartz grains are small, some are sub-angular
- Voids generally small and confined to the matrix
- Voids mostly lined with granular spar, some dogtooth spar as well
 - Dogtooth spar is associated with dissolution lining of skeletal voids
- Micrite matrix mostly intact
- Largest void ~4mm x 2mm
- Glauconite and quartz are clastic
- Possibly a long fibrous anhydrite crystal
- Fossils are well preserved
 - Very little skeletal dissolution

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Authigenic pyrite formed in matrix
- Lime mud lithification to micrite
- Calcite replacement of echinoderms and corals
- Microspar replacement of bryozoan skeletons and foraminifera
- Dissolution of matrix with reprecipitation of micrite in voids

Slide: TSL4-6

General Description

Micrite matrix; bryozoans; foraminifera; echinoderms; bivalves; solution seams; opaques; glauconite; intraclasts; quartz; gastropods; biomicrudite

Fossil Descriptions

Bivalves:

- Dissolution of shells
- Partial filling with dogtooth and granular spar

Bryozoans:

- Micrite skeletal replacement
- Void filling with microspar and some dissolution

Echinoderms:

- Spar replacement of plates

Gastropods:

- Voids micrite filled
- Shells dissolved and lined with granular spar

Observational Notes

- Solution seams dissolved and expanded
 - Lined with granular spar
- Minimal glauconitization of micritic matrix

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Authigenic pyrite formed in matrix
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates with some syntaxial overgrowths
- Microspar and micrite replacement of bryozoan skeletons and foraminifera
- Dissolution of bivalve shells
- Lining of bivalve molds with granular spar and micrite
- Glauconitization in matrix
- Dissolution of matrix

Slide: TSL4-SL3

General Description

Micrite matrix; bryozoans; echinoderms; gastropods; bivalves; glauconite; opaques; glauconitization; quartz; intraclasts; biosparrudite

Fossil Descriptions

Gastropods:

- Micrite filled voids
- Microspar has replaced shells

Bivalves:

- Dissolved shells
- Dogtooth and granular spar linings
- Some partially to mostly filled voids
- Other voids show vuggy fabric development

Bryozoans:

- Micrite skeletal replacement
- Voids filled with microspar
- Some exhibit extensive glauconitization of voids

Echinoderms:

- Calcite replacement of plates

Observational Notes

- Some pyritization
- Good deal of glauconitization throughout, including in the matrix
- Matrix has undergone neomorphism to microspar
- Vuggy porosity developed

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Authigenic pyrite formed in and adjacent to bryozoans and glauconite grains
- Lime mud lithification to micrite
- Calcite replacement of echinoderms with some syntaxial overgrowths
- Microspar replacement of bryozoan skeletons and gastropod shells
- Dissolution of bivalve shells
- Granular spar linings in bivalve molds
- Filling of bivalve molds with granular spar
- Micrite matrix neomorphism to microspar

- Micrite in bryozoans has undergone neomorphism to microspar
- Glauconitization of microspar in bryozoans and of calcite in some echinoderms
- Dissolution in matrix created vuggy fabric

Slide: TSL5

General Description

Micrite matrix; bivalves; gastropods; echinoderms; foraminifera; bryozoans; quartz grains; opaques; glauconite pellets; glauconitization – mainly of bryozoans; some glauconitization of the matrix; coral; biosparrudite

Fossil Descriptions

Bivalves:

- Shell dissolution
- Voids lined with dogtooth and granular spar

Gastropods:

- Micrite void fillings
- Shells dissolved
 - Replaced with granular spar
- Minimal gastropods

Echinoderms:

- Spar calcite replacement of plates

Bryozoans:

- Micrite filled voids
- Skeletons replaced with micrite
- Void micrite neomorphism to microspar
 - Some glauconitized
 - Some also appear pyritized

Foraminifera:

- Micritized in the matrix

Coral:

- Shell dissolution
 - Filled with dogtooth and granular spar
- Voids filled with micrite

Observational Notes

- Many voids unrecognizable as to original shell forms
- Vuggy fabric has developed
- Micrite matrix mostly intact but neomorphism to microspar around voids and some allochems
- Extensive dogtooth spar along void linings
- Possibly a few dolomite rhombs in linings
- Filled fracture
 - Dissects glauconite nodule
 - Filled with granular spar

Diagenetic Activity

- Breakage of shells and skeletons during deposition
- Authigenic pyrite formed in and adjacent to bryozoans
- Micrite envelopes formed
- Lime mud lithification to micrite
- Calcite replacement of echinoderm plates and coral
- Microspar and micrite replacement of bryozoans and foraminifera
- Dissolution of bivalve and gastropod shells
- Bivalve and gastropod molds lined with dogtooth and granular spar
- Bivalve and gastropod voids filling with granular spar
- Bryozoan micrite in voids has undergone neomorphism to microspar
- Glauconitization has begun in microspar in bryozoans and matrix
- Matrix micrite has undergone neomorphism to spar
- Dissolution of matrix has begun

Appendix C: Hand Specimen Descriptions

SL1-15: Well-cemented, light gray wackestone. Bivalve molds to 5mm; gastropod shells to 5mm; bryozoan fans and skeletal parts to 5mm; dark nodules less than 1mm are evident.

SL1-35: Well-cemented, light to medium gray packstone. Bryozoan skeletal parts and fans to 10mm; bivalve molds to 5mm. Layering of bioclasts and a possible solution seam are evident. Visible voids 1 to 3mm and 1mm phosphatic nodules also apparent.

SL2-40: Well-cemented, very light gray wackestone. Bivalve molds to 12mm and bryozoan skeletal parts to 10mm. Very small phosphatic nodules, less than 1mm are common. Voids to 3mm are evident. Layering is apparent.

SL3-18: Well-cemented, light gray packstone. Sand dollars to 20mm, bryozoan skeletal parts to 10mm, bivalve molds to 20mm and gastropod shell parts to 5mm are present. Layering, voids to 5mm and phosphatic nodules to 2mm are also evident.

SL3-25: Very crumbly, medium to dark gray grainstone. Visible bryozoan skeletal parts and coral fragments 1 to 5mm in size; bivalve molds 1 to 5mm. Spar coatings on grains visible using hand lens. Phosphatic nodules 1 to 2mm are common.

SL3-30: Well-cemented, light gray packstone. Bryozoan skeletal parts to 30mm and bivalve molds to 10mm are evident. Layering is present as are voids to 5mm and <1mm phosphatic nodules.

SL4-15: Dense, well-cemented, very light gray wackestone. Bivalve shells and molds to 40mm; bryozoan skeletal parts to 4mm. 1mm voids, very common 1mm phosphatic nodules and layering are present.

SL4-25: Well-cemented, very light gray packstone. Bivalve molds to 15mm and bryozoan skeletal parts to 5mm evident. Layering is evident as are voids to 3mm.

SL5-55: Well-cemented, very light gray packstone. Bivalve molds to 10mm, bryozoan skeletal parts to 5mm and gastropod shells to 1mm are present. Layering is present as are phosphatic nodules to 2mm and voids to 4mm.

SL5-70: Dense, well-cemented, light gray wackestone. Bivalve molds and bryozoan skeletal parts 1 to 20mm. 1 to 3mm voids and phosphatic nodules 1 to 2mm are evident.

SL5-70R: Well-cemented, light gray packstone. Bivalve molds to 20mm; bryozoan skeletal parts to 20mm; voids up to 10mm. Sparse phosphatic nodules 1 to 4mm. Layering of bioclasts is evident.

SL6-80: Dense, well-cemented, light gray packstone. Bivalve molds to 3mm and phosphatic nodules to 3mm are evident. A few visible voids to 1mm.

SL6-98: Mildly crumbly, medium gray grainstone/packstone. Bryozoan skeletal parts to 5mm; bivalve molds to 15mm. Voids to 2mm and phosphatic nodules to 3mm are present. Layering is evident.

TSL1: Well-cemented, light brown packstone. Bivalve molds to 20mm and bryozoan skeletal parts to 10mm are very common. Layering of bioclasts is quite evident. Visible voids to 5mm and phosphatic nodules to 2mm are present.

TSL2-SL4: Well-cemented, light gray packstone. Bryozoan skeletal parts to 20mm and bivalve molds to 5mm are present. Layering of bioclasts is evident. Visible voids 1 to 3mm and phosphatic nodules to 2mm also present.

TSL3: Well-cemented, light brown packstone. Sand dollars to 40mm, bivalve molds to 35mm and bryozoan skeletal parts to 10mm are evident. Voids to 3mm are present.

TSL3+100: Poorly-cemented, light brown packstone. Bryozoan skeletal parts to 30mm and bivalve molds to 20mm with possible echinoids to 40mm. Very minimal <1mm voids and phosphatic nodules.

TSL4-6: Well-cemented, light brown packstone. Bryozoan skeletal parts to 20mm and voids to 10mm are present.

TSL4-SL3: Well-cemented, reddish-brown packstone. Bryozoan skeletal parts and bivalve molds to 10mm. Layering is quite evident and voids to 1mm are present.

TSL5: Well-cemented, reddish-brown packstone. Bivalve molds and shells to 10mm, gastropod shells to 10mm and bryozoan skeletal parts to 20mm are present. Layering is present as are voids to 10mm.

HS1-55: Well-cemented, very light gray grainstone. Bivalve molds and bryozoan skeletal parts to 20mm and gastropod shell parts to 5mm. Layering is evident as are voids to 3mm and 1mm phosphatic nodules.

HS2-65: Poorly-cemented, very light brown packstone; 1 to 5mm bryozoan skeletal parts; layering of bioclasts is evident; no voids visible. A few phosphatic nodules to 1mm are evident.

Appendix D: Point Count Value Charts

Matrix Point Count Values and Percentages by Depth

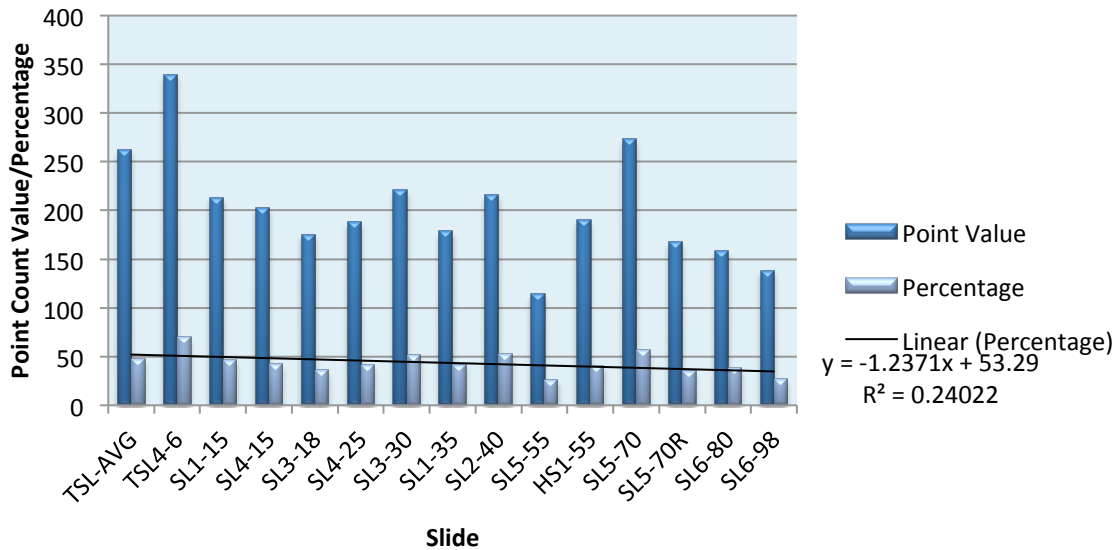


Chart D1 – Point Count Values and Percentages for Micritic Matrix

Void Point Count Values and Percentages by Depth

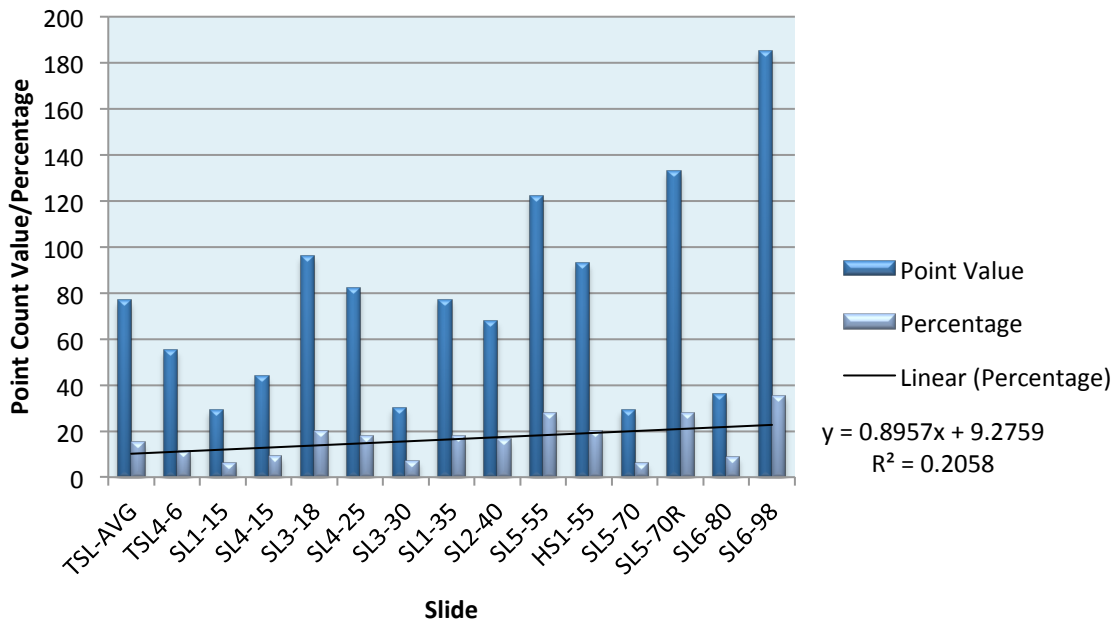


Chart D2 – Point Count Values and Percentages for Matrix Void Spaces

Echinoderm Point Count Values and Percentages by Depth

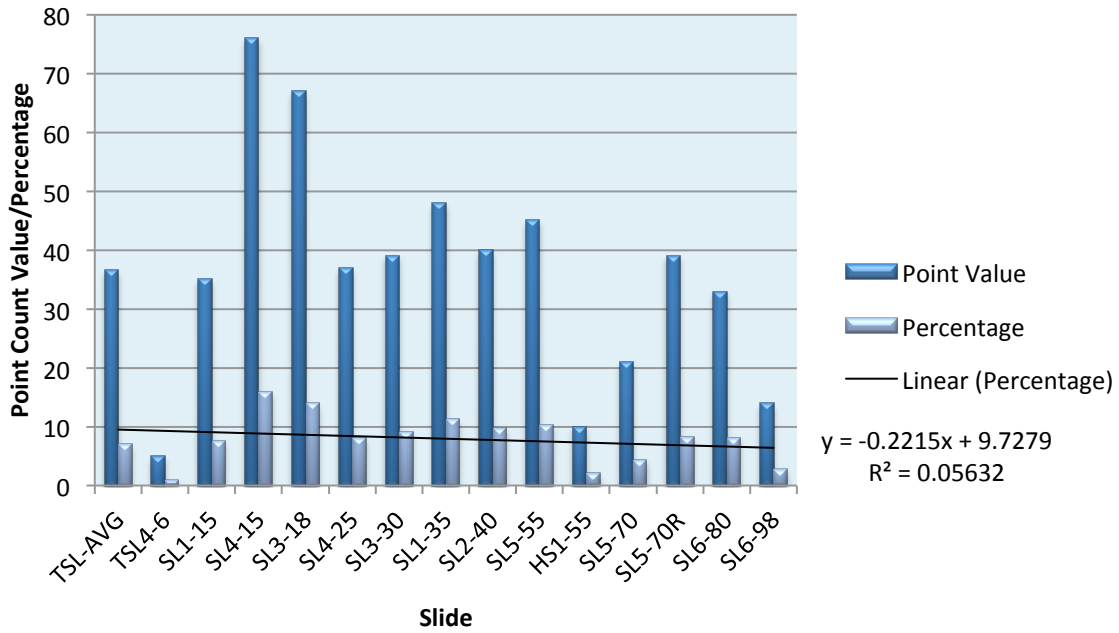


Chart D3 – Point Count Values and Percentages for Echinoderms

Bryozoan Point Count Values and Percentages by Depth

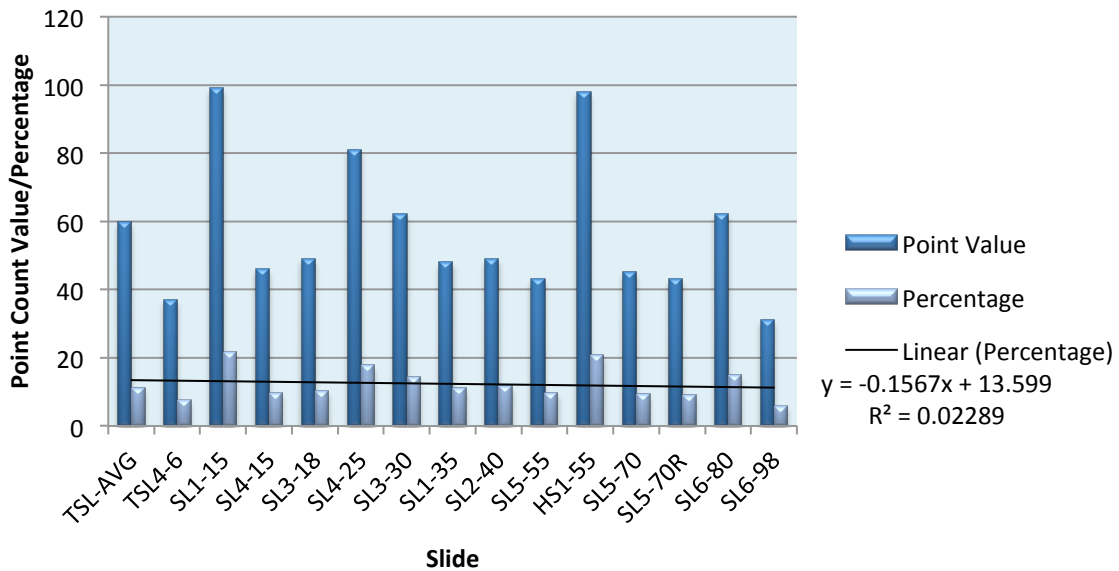


Chart D4 – Point Count Values and Percentages for Bryozoans

Bivalve Point Count Values and Percentages by Depth

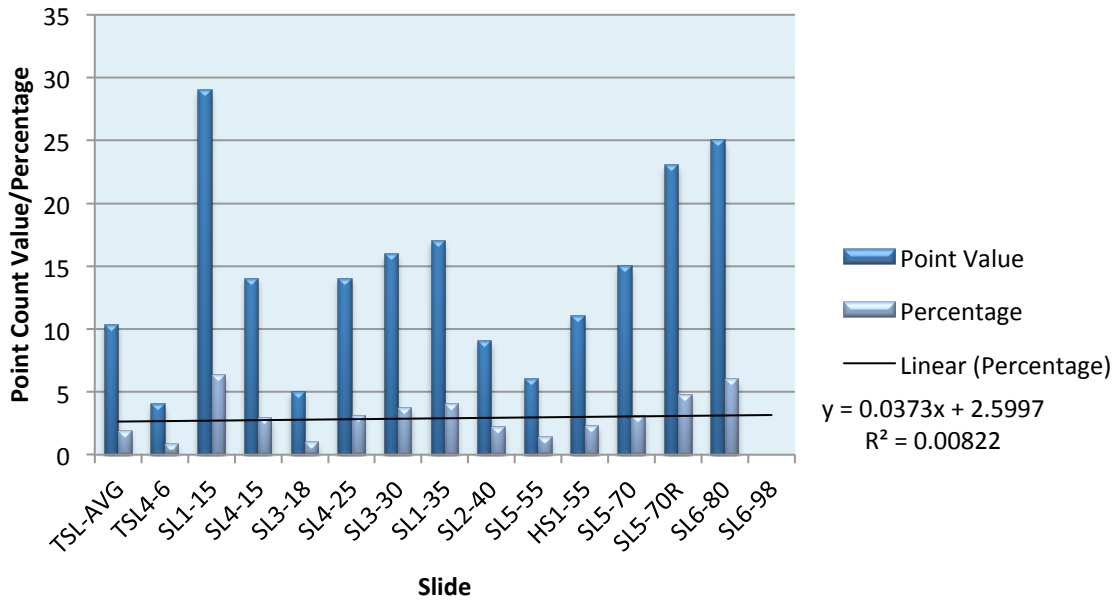


Chart D5 – Point Count Values and Percentages for Bivalves

Gastropod Point Count Values and Percentages by Depth

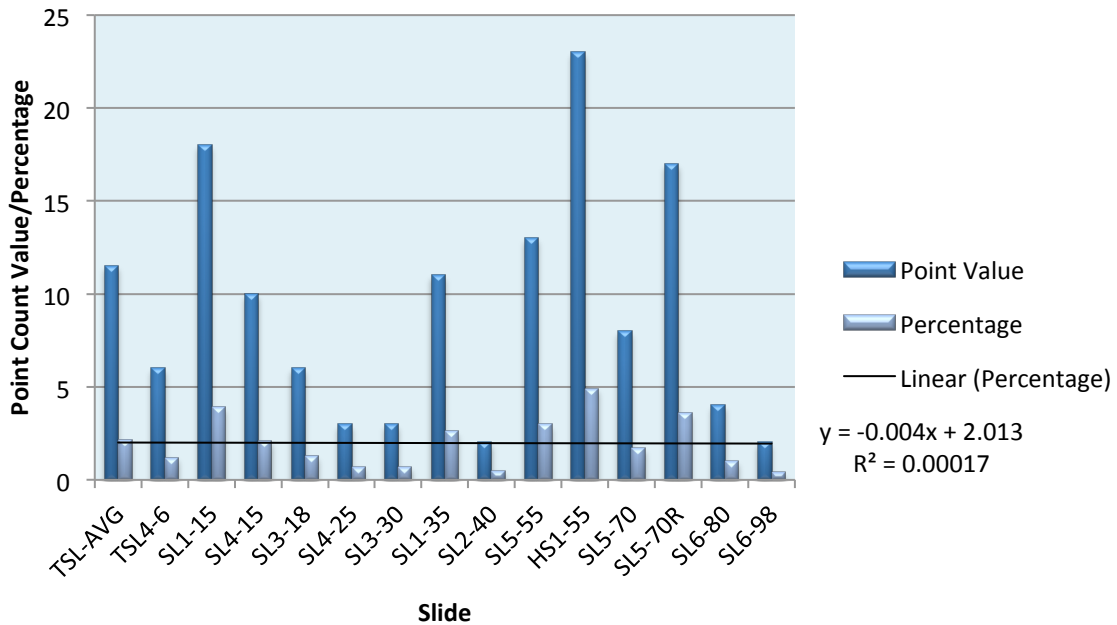


Chart D6 – Point Count Values and Percentages for Gastropods

Foraminifera Point Count Values and Percentages by Depth

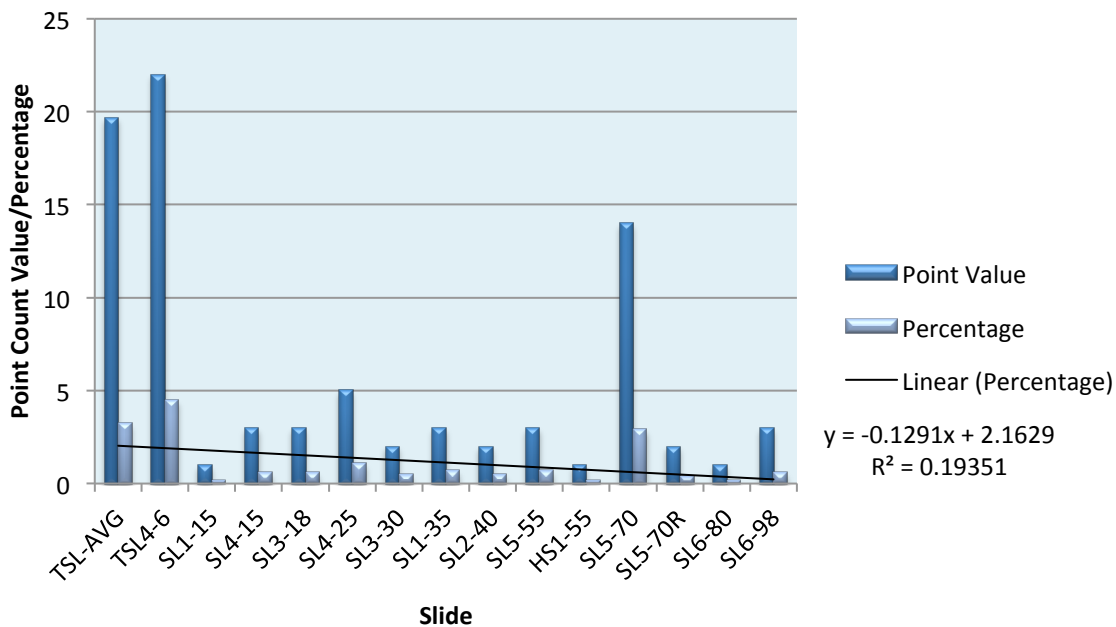


Chart D7 – Point Count Values and Percentages for Foraminifera

Quartz Point Count Values and Percentages by Depth

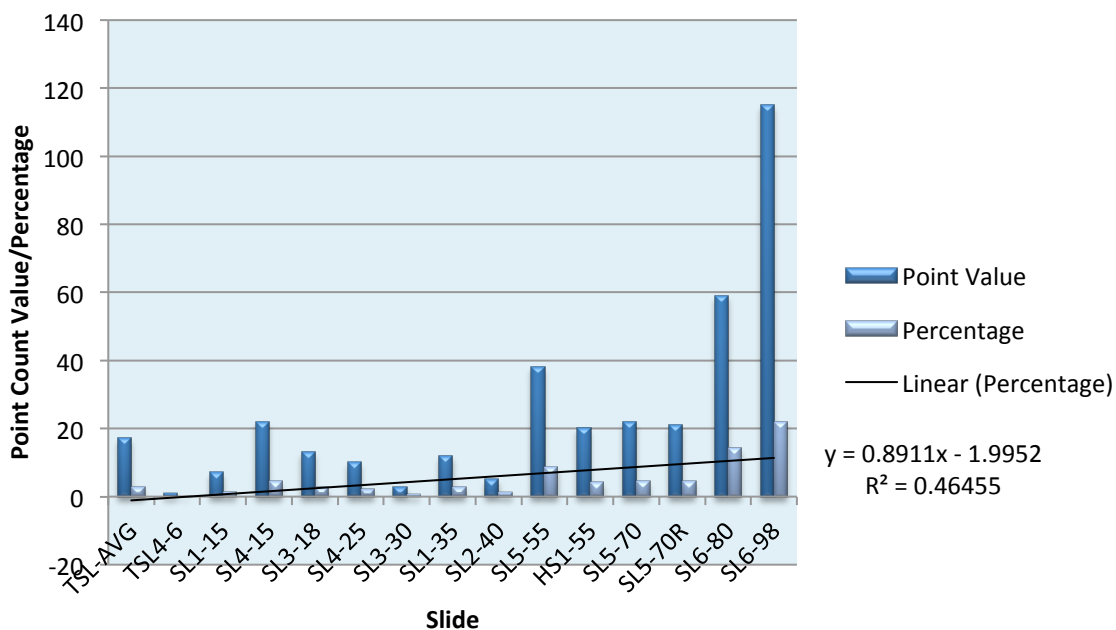


Chart D8 – Point Count Values and Percentages for Quartz

Glauconite Point Count Values and Percentages by Depth

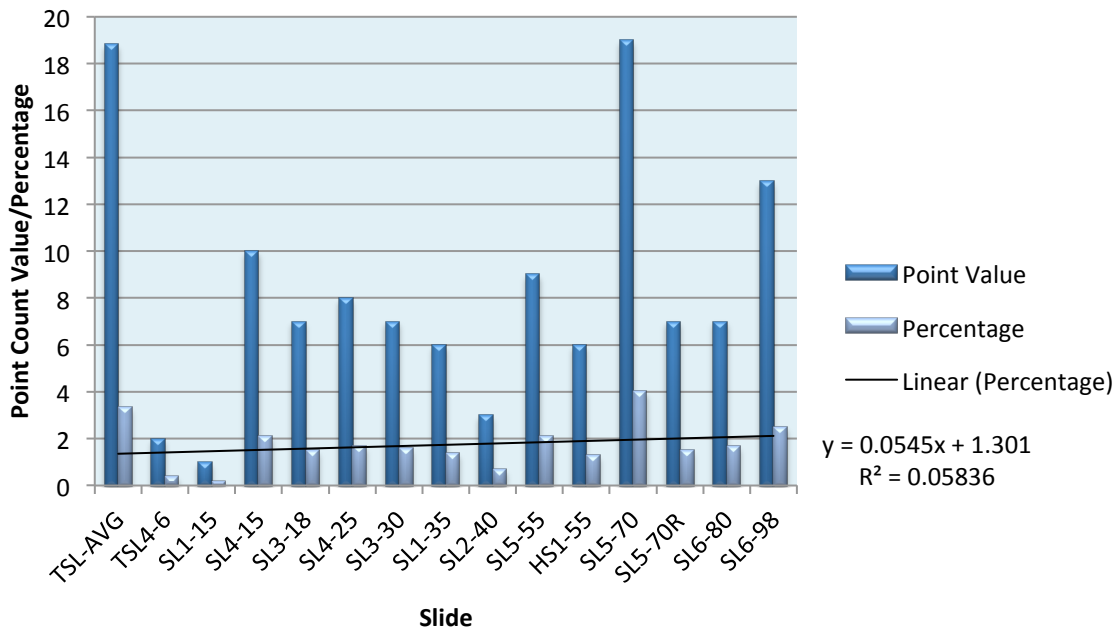


Chart D9 – Point Count Values and Percentages for Glauconite

Other Intraclasts Point Count Values and Percentages by Depth

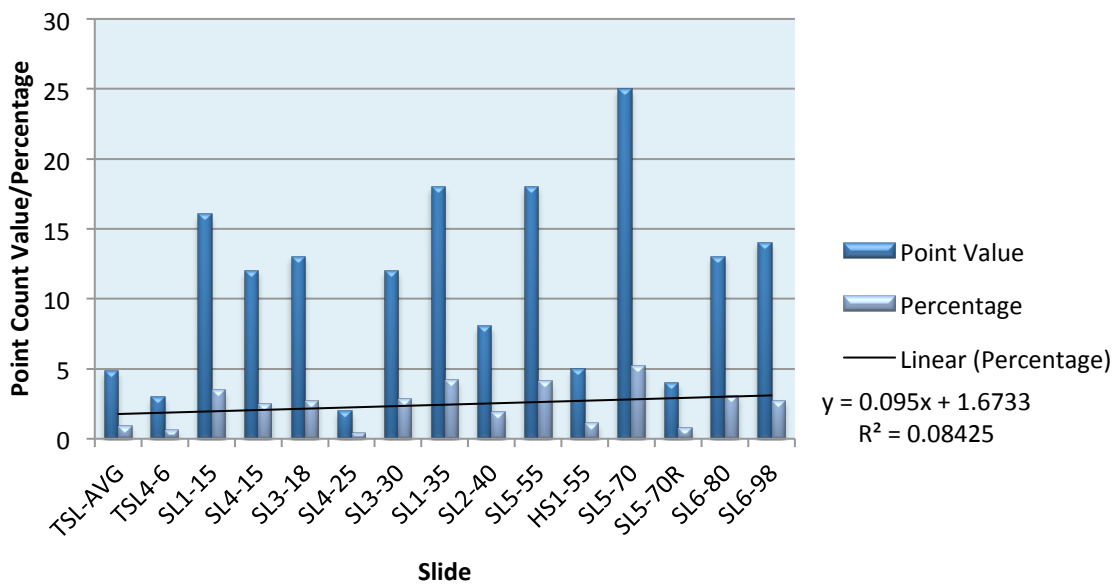


Chart D10 – Point Count Values and Percentages for Other Intraclasts

Unidentified Bioclasts Point Count Values and Percentages by Depth

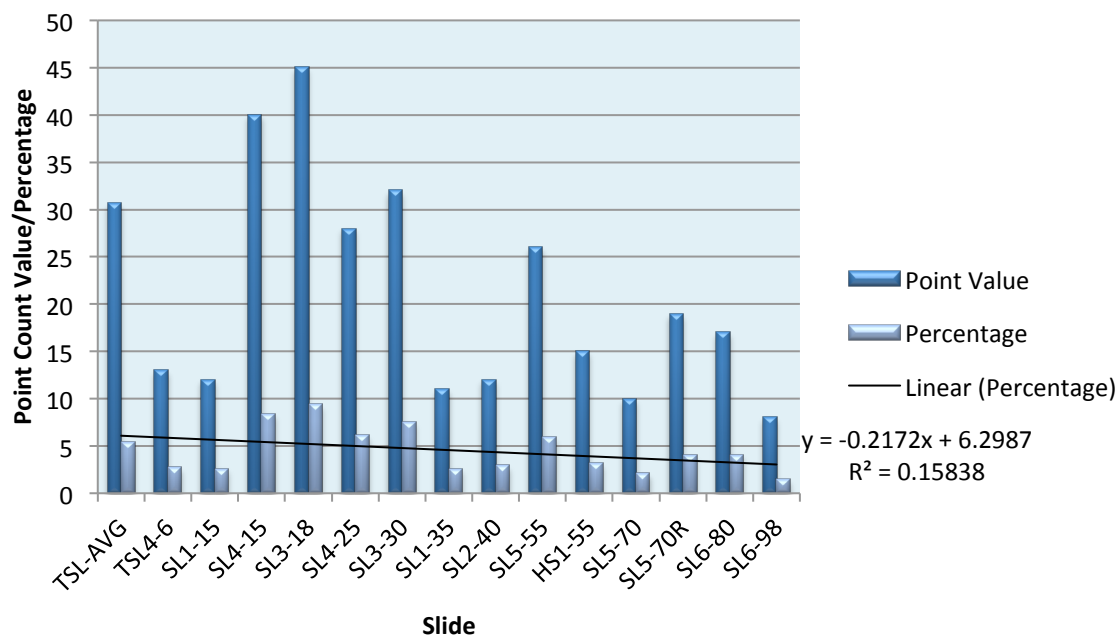


Chart D11 – Point Count Values and Percentages for Unidentified Bioclasts

Appendix E: Lithologic Unit Descriptions

Grainstone/Packstone-1: This layer is a medium gray, vuggy, well-cemented grainstone-packstone/biosparrudite represented by sample SL6-98. It is below the active floor of the quarry. It contains bryozoans, gastropods and echinoderms. This layer also has high quartz content (22.0%), the highest of any limestone layer. The quartz appears to be detrital. This layer is at least 4ft thick and is possibly the lowermost carbonate layer at the quarry. Percentages for major constituents and void space are as follows: matrix (26.4%), void space (35.4%), echinoderms (2.7%), bryozoans (5.9%), bivalves (0.0%), gastropods (0.4%), quartz (22.0%) and glauconite (2.5%); pyrite is also in evidence.

Carbonate Sand-1: This layer is approximately 8ft thick and below the active floor of the quarry. There is no representative sample from this layer. From field inspection it was found to be a medium gray, very poorly consolidated carbonate sand. It consists mostly of well-rounded bryozoan skeletal parts.

Wackestone-1: This layer is represented by samples SL5-70 and SL6-80. It is a light gray, dense, well-cemented wackestone with bryozoans, echinoderms, bivalves and gastropods. The upper section is a biomicrudite while the lower section is a biosparrudite. The bioclasts are well rounded and some have micrite envelopes. The bivalve molds are generally larger in the upper part of this layer. Cross-bedding is also present; the layer is approximately 20ft thick. Chart 1 shows the major constituents of the layer. As shown on Chart E1, the percentages of bryozoans, echinoderms, bivalves and quartz increases with depth. In addition to glauconite, pyrite is also present.

Component	SL5-70	SL6-80
Bryozoans	9.4%	14.9%
Echinoderms	4.4%	8.0%
Bivalves	3.1%	6.0%
Gastropods	1.7%	1.0%
Glauconite	4.0%	1.7%
Quartz	4.6%	14.2%
Matrix	56.8%	38.1%
Void Space	6.0%	8.7%

Chart E1 – Component Percentages for Wackestone-1

Grainstone/Packstone-2: This layer is represented by samples SL5-55, HS1-55 and HS2-65 and possibly SL5-70R. It is approximately 15ft thick and is primarily a light gray/light brown packstone/biosparrudite. Bivalves, bryozoans, gastropods and echinoderms are all common in this layer. Bryozoans are the most common bioclasts, ranging from 10% to 21%. The major constituents are shown on Chart E2. Point counts are not reported for HS2-65 as no thin section was made. Micrite envelopes are evident surrounding several gastropod shells and bivalve molds.

Component	SL5-55	HS1-55	SL5-70R
Bryozoans	9.8%	20.8%	9.0%
Echinoderms	10.3%	2.1%	8.2%
Bivalves	1.4%	2.3%	4.8%
Gastropods	3.0%	4.9%	3.6%
Glauconite	2.1%	1.3%	1.5%
Quartz	8.7%	4.2%	4.4%
Matrix	26.1%	40.3%	35.3%
Void Space	27.9%	19.7%	27.9%

Chart E2 – Component Percentages for Grainstone/Packstone-2

Carbonate Sand-2: This unit was inspected in the field. It is a medium gray, very poorly-cemented carbonate sand that consists of well-rounded bryozoan skeletal parts and coral fragments. It is approximately 8ft thick.

Wackestone-2: This layer is represented by samples SL1-35 and SL2-40. The layer changes from a light gray, well-cemented wackestone/biomicrudite in the lower section to a medium gray, well-cemented packstone in the upper part. Fossils include bryozoans, bivalves, echinoderms and foraminifera. Constituent percentages are included on Chart E3. In addition to the fossils, glauconite and pyrite are also present, as are cross-bedding and layering of bioclasts. The layer is approximately 10 feet thick.

Component	SL1-35	SL2-40
Bryozoans	11.2%	11.8%
Echinoderms	11.2%	9.7%
Bivalves	4.0%	2.2%
Gastropods	2.6%	0.5%
Glauconite	1.4%	0.7%
Quartz	2.8%	1.2%
Matrix	41.5%	52.2%
Void Space	17.9%	16.4%

Chart E3 – Component Percentages for Wackestone-2

Carbonate Sand-3: This layer was inspected during field study. It is a medium gray, crumbly carbonate sand layer with well-rounded bryozoan grains. It is approximately 3 to 5 feet thick.

Packstone-1: SL3-30 is the representative sample for this layer, which is approximately 5ft thick. It is a light gray, well-cemented bryozoan-rich packstone/biomicrudite. The bryozoan skeletal parts are up to 30mm in size. It also contains bivalve molds, gastropods, echinoderms and foraminifera. Bryozoans are the dominant bioclasts comprising 14.5% of the sample. The quartz content is extremely low (0.7%). Other constituents include echinoderms (9.1%), bivalves (3.7%), gastropods (0.7%), glauconite (1.6%), matrix (51.8%) and void space (7.0%); pyrite is

also present. Micrite envelopes surround some of the bivalve molds; layering of bioclasts and cross-bedding are also evident.

Carbonate Sand-4: This layer is represented by sample SL3-25. It is a medium gray, bryozoan-rich, very poorly-cemented carbonate sand, approximately 10ft thick. The grains are minimally cemented by meniscus granular cements. Bioclasts in this layer are well-rounded. In addition to bryozoans the sand size grains include gastropod and coral fragments. In hand specimen this layer is very crumbly.

A change is evident at the 45ft level below the land surface approximately 200ft to the west at sampling location SL4. Sample SL4-25 is a light gray well-cemented packstone showing layering of the bioclasts and cross-bedding. Bryozoans are the primary bioclasts, comprising 17.7% of the layer. Echinoderms (8.1%), bivalves (3.1%), gastropods (0.7%) and pyrite are also present. The quartz content is low (2.2%).

Packstone-2: This layer is represented by sample SL3-18. It is a light gray, well-cemented, approximately 5ft thick packstone/biosparrudite layer with echinoderms (14.0%), bryozoans (10.2%), gastropods (1.3%), quartz (2.7%), glauconite (1.5%), bivalve molds (1.0%) and pyrite. The matrix comprises 36.5% and void space accounts for 20.0% of the volume. This layer also contains 9.4% unidentified bioclasts. These may possibly be coral fragments, echinoderms or other highly damaged bioclasts.

Packstone-3: Samples SL1-15 and SL4-15 are representative of this layer. It is a light gray, well-cemented packstone/biomicrodite, approximately 5ft thick. Fossils include bryozoans, echinoderms, gastropods and bivalve molds. Bryozoans and echinoderms are the dominant bioclasts. It contains the only ooid found in the study. Layering of bioclasts, cross-bedding, glauconite and pyrite are present in this layer.

Bivalve molds are large in this layer, up to 40mm. A summary of the major constituents is shown on Chart E4.

Component	SL1-15	SL4-15
Bryozoans	21.5%	9.6%
Echinoderms	7.6%	15.9%
Bivalves	6.3%	2.9%
Gastropods	3.9%	2.1%
Glauconite	0.2%	2.1%
Quartz	1.5%	4.6%
Matrix	46.3%	42.2%
Void Space	6.3%	9.2%

Chart E4 – Component Percentages for Packstone-5

Poorly Indurated Wackestone (Marl)

The representative field samples are DC-33 and DC-38. It is light brown and approximately 5 to 10ft thick in the eastern section of the north quarry. Large (40mm) bryozoan skeletal fragments are evident in the lower part while smaller ones (less than 10mm) are present in the upper section. The siliciclastic silt content is 10%. It is semi-consolidated but the matrix readily disintegrates in water. Occasional voids in the matrix are up to 5mm. A change to sand/marl and then sand are seen (Fig. 25).

Packstone-4

This is the topmost rock layer present at the quarry. It is represented by samples TSL1, TSL2-SL4, TSL3, TSL3+100, TSL4-SL3, TSL4-6 and TSL5. It is a light gray/light brown/reddish-brown, well-cemented packstone/biomicrudite. Bryozoans, bivalves, gastropods, and echinoids are present. Shark teeth are also present. This is the only layer in which they are evident. Phosphate nodules up to 10mm are present in this layer. Sample TSL4-SL3 shows layering of bioclasts. Bryozoans range from less than 4% in sample TSL3 to almost 23% in sample TSL5. Echinoderms range from 1% in

TSL4-6 to greater than 13% in TSL1. The percentage of bivalves is low; sample TSL1 showed none. The highest percentage is 5.4% in sample TSL5. Gastropods range from less than 1% in sample TSL3 to greater than 4% in TSL4-SL3. Glauconite is also evidenced in low amounts, from lower than 1% in TSL4-6 to more than 5% in TSL3 and TSL3+100. Pyrite is present in and around bioclasts. Chart E5 shows the percentages for many of the components.

<i>Component</i>	<i>TSL1</i>	<i>TSL2-SL4</i>	<i>TSL3</i>	<i>TSL3+100</i>	<i>TSL4-SL3</i>	<i>TSL4-6</i>	<i>TSL5</i>
Bryozoans	12.7%	11.2%	3.6%	5.7%	11.6%	7.6%	22.9%
Echinoderms	13.4%	11.2%	4.9%	2.5%	7.5%	1.0%	2.7%
Bivalves	0.0%	3.6%	0.6%	0.4%	1.2%	0.8%	5.4%
Gastropods	1.2%	2.1%	0.4%	1.9%	3.7%	1.2%	3.4%
Glauconite	3.4%	3.7%	5.2%	5.3%	2.1%	0.4%	0.4%
Quartz	0.7%	3.9%	3.3%	6.0%	2.7%	0.2%	1.4%
Matrix	28.0%	49.9%	52.9%	53.9%	50.9%	69.6%	45.2%
Void Space	34.6%	8.5%	10.5%	9.4%	12.6%	11.3%	14.5%

Chart E5 – Component Percentages for the Upper Packstone Unit

Appendix F: Unit Diagenetic Descriptions

The diagenetic history of each unit is described in the following section. The diagenetic activity of each unit can be separated into three relative time stages, early, middle and late (Chart F1).

	<i>Early</i>	<i>Middle</i>	<i>Late</i>
Earlier	Micrite envelopes Authigenic pyrite	Mold filling Matrix/shell neomorphism	Dissolution of matrix/shells Dogtooth/granular spar cement linings
↓	Lithification		
Later	Shell replacement		

Chart F1 – Diagenetic Activities

Grainstone/Packstone-1: After lithification of the lime mud into micrite, there has been calcite replacement of echinoderm plates, microspar replacement of bryozoan skeletons and gastropod shells and possible dissolution of bivalve shells. Prior to lithification authigenic pyrite formed in and around bryozoan skeletons. Dissolution of gastropod shells occurred next, followed by complete neomorphism of the micrite matrix to spar creating the current spar matrix. Dissolution of the spar matrix then began, creating a vuggy fabric. Dogtooth and granular spar cement linings are seen as the last diagenetic event, having occurred in the meteoric phreatic and/or vadose zones.

Carbonate Sand-1: The diagenetic features were not studied.

Wackestone-1: Prior to lithification micrite envelopes formed around some of the bivalve shells followed by the formation of authigenic pyrite in and near bryozoan skeletons and glauconite pellets. While the layer was still in the marine phreatic zone bivalve shell dissolution took place as did micrite replacement of bryozoan skeletons, calcite replacement of echinoderms, some with syntaxial overgrowths and microspar replacement of gastropod shells. Bivalve molds were then filled with granular spar,

possibly while still in the marine phreatic zone. Next the layer was exposed to the meteoric zones and the micrite matrix began to undergo neomorphism to spar. This neomorphism is most prominent in the lower part of the layer. Some degrading neomorphism of granular spar to micrite has occurred in some of the bivalve molds. Dissolution of matrix has also occurred, mostly in the lower part. Lastly, dogtooth and granular spar cements have lined many of the matrix and shell voids.

Grainstone/Packstone-2: Early diagenesis included the formation of micrite envelopes around some of the bioclasts. Then authigenic pyrite formed in and near bryozoan skeletons and glauconite grains and then the lime mud was lithified. While in the marine phreatic zone, bryozoan skeletons and gastropod shells were replaced by micrite and/or microspar and echinoderms were replaced by spar with some syntaxial overgrowths. Bivalve shells dissolved during this stage, resulting in molds with some filling by microspar. When the layer was exposed to the meteoric phreatic zone, neomorphism of matrix to microspar/spar began. Dissolution of microspar in molds and gastropod shells also occurred along with some dissolution of matrix and bioclasts. The layer was then exposed to the meteoric vadose zone where dissolution of matrix and bioclasts occurred. Dogtooth and granular spar linings of voids also began to form during this stage.

Carbonate Sand-2: As with Carbonate Sand-2, diagenetic features were not studied.

Wackestone-2: In the marine phreatic zone authigenic pyrite formed in and around bryozoan skeletons and glauconite grains and lime mud lithified. Bivalve shells were then dissolved, bryozoan skeletons and gastropods were replaced by microspar and

echinoderms were replaced by spar with some syntaxial overgrowths. Bivalve molds were then filled with microspar either in the marine phreatic or after the layer shifted to the meteoric phreatic zone. In the meteoric phreatic zone dissolution of microspar in gastropods and bivalves occurred. Mold and shell dissolution has extended into the matrix beyond the original borders of the shells. The layer then shifted to the meteoric vadose zone where dogtooth and granular spar have formed linings in the void spaces.

Carbonate Sand-3: This layer was only inspected during field sampling and diagenetic features were not studied. The lack of consolidation indicates the absence of grain binding cementation.

Packstone-1: Diagenesis began with the formation of authigenic pyrite in and near bryozoan skeletons. While still in the marine phreatic zone, lithification of the lime mud took place. Bivalve shells then dissolved, echinoderms were replaced by spar and bryozoans were replaced by micrite and microspar. When the layer was exposed to the meteoric phreatic zone the micritic matrix began neomorphism to microspar; micrite and microspar which had earlier replaced bryozoan skeletons dissolved, and dogtooth and granular spar lined void spaces. Some micritic microspar also dissolved late in this stage.

Carbonate Sand-4: The diagenetic features for the carbonate sand component of this layer are confined to meniscus cements and dogtooth and granular spar coatings. The higher porosities have allowed pore waters to flow more freely through the sand layers reducing the residence time for dissolved ions to interact with the bioclastic grains.

The packstone, however, does show evidence of extensive diagenesis. Micrite envelopes formed around some shells and skeletons while they were still on the seafloor prior to lithification. Authigenic pyrite formed around bryozoan skeletons prior to lithification. While in the marine phreatic zone echinoderm skeletons were replaced by spar; micrite replaced bryozoan skeletons; microspar replaced gastropod shells and bivalve shells were dissolved. The layer subsequently shifted to the meteoric marine zone. While in this zone dissolution of gastropod shells occurred. Neomorphism of micrite in bryozoans to microspar also occurred. The layer was then either exposed to the meteoric vadose zone or experienced an influx of freshwater. This change resulted in the dissolution of matrix which has created the vuggy fabric. Radial mineral growths also occurred during this stage. These growths may possibly have been anhydrite or gypsum.

Packstone-2: Burrowing organisms caused micrite envelopes to form around many bioclasts, this was followed by the formation of authigenic pyrite in and near bryozoan skeletons and then lithification. In the marine phreatic zone, bivalve shells dissolved, microspar replaced bryozoans and spar replaced echinoderms with some syntaxial overgrowths. When the layer was exposed to the meteoric phreatic zone, the micritic matrix and microspar in bryozoans underwent neomorphism to spar and voids expanded beyond the boundaries of the original shells. When the layer was exposed to the meteoric vadose zone, dogtooth and granular spar linings formed on the surface of the voids.

Packstone-3: Diagenesis began with the formation of micrite envelopes followed by the formation of authigenic pyrite. Lithification of the lime mud then occurred. In the

marine phreatic zone, bryozoan skeletons were replaced by microspar and micrite, echinoderms were replaced by spar with some syntaxial overgrowths, bivalve shells dissolved leaving behind molds and gastropod shells were replaced by microspar. The layer then probably shifted to the meteoric phreatic zone where some neomorphism of micritic matrix to microspar and spar occurred. After exposure to the meteoric vadose zone, dogtooth and granular spar linings formed in void spaces.

Poorly Indurated Wackestone (Marl)

Diagenesis in the marl layer has been confined to compaction of the lime mud.

Packstone-4

Micrite envelopes are the earliest recognizable diagenetic feature seen in this unit. The formation of authigenic pyrite in and near bryozoan skeletons and glauconite grains was followed by the lithification of lime mud. In the marine phreatic zone, bivalves dissolved, bryozoans and gastropods were replaced by micrite and microspar and echinoderms were replaced by spar calcite. Two divergent diagenetic sequences are then evident. One sequence included neomorphism of micritic matrix to microspar and spar followed by dissolution of matrix and increases in voids associated with shells and skeletons. Void linings were then coated with dogtooth and granular spar. The other sequence includes little to no neomorphism of the micritic matrix and shows only minimal dogtooth and granular spar linings. The probability exists that the samples in the second sequence spent little time in the meteoric phreatic zone.

